ANNEXES

Effects of Dynamic Speed Limit strategies on capacity at Freeway Bottlenecks

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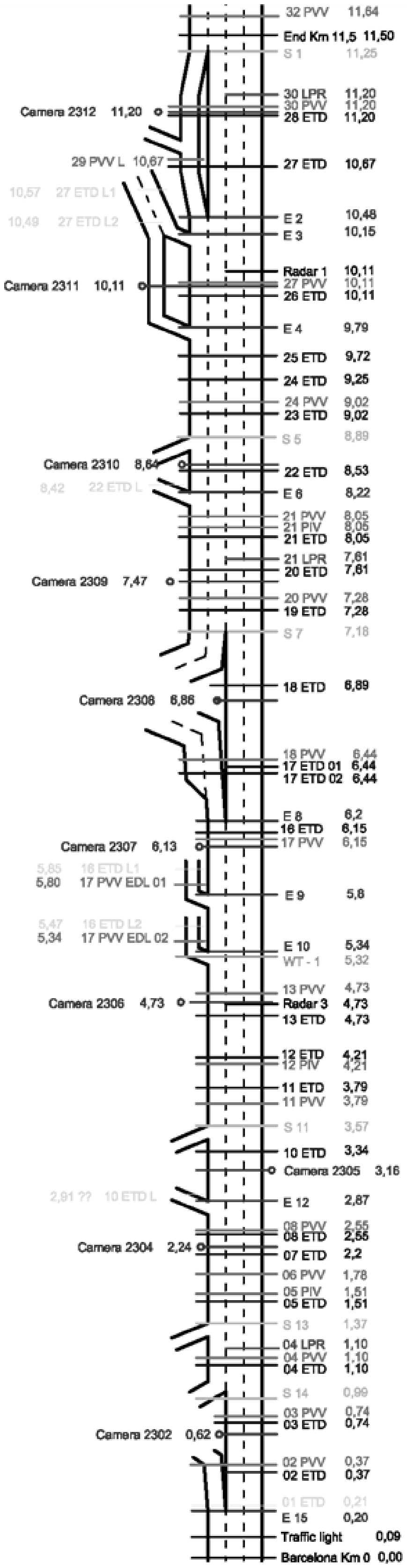
A. Layout B-23



Legend

PVV	*Dynamic speed limit*
ETD	*Loop detector*
E	*On-ramp*
S	*Off-ramp*
LPR	*License plate recognition*
PIV	*Variable message sign*

Figure 1: Layout B-23

B. Fixing errors

Peaks Error

We detected some mistakes when we began to work with the data. One of the first things we did was plot the different data of the different loop detectors during all day and we noticed that there were abnormal peaks. This peaks could only be produced for a Data Error. That is why we proceeded to fix it. These errors happened in two of the three data types: vehicle counts and occupancy.

This error could be produced for some mistake in the measure equipment or misconfiguration of the device, but we were not able to clarify the exact reason that caused it.

<u>Vehicle counts</u>

The counting of vehicles data are affected for this type of error. In total there are 5 loop detectors with peak errors in vehicle counts data. We considered there was an Error when the vehicle counts value is much larger of 50 veh/min per lane, i.e. more than 100 veh/min. (There is not any case within values between 100 and 50.)

In the following figures we can see the place and time when it occurs (LDs and time). The X-axis represents the hours of the day while the Y-axis is the vehicle counts per lane in aggregated data of one minute. Each different color represents the data of one different lane.

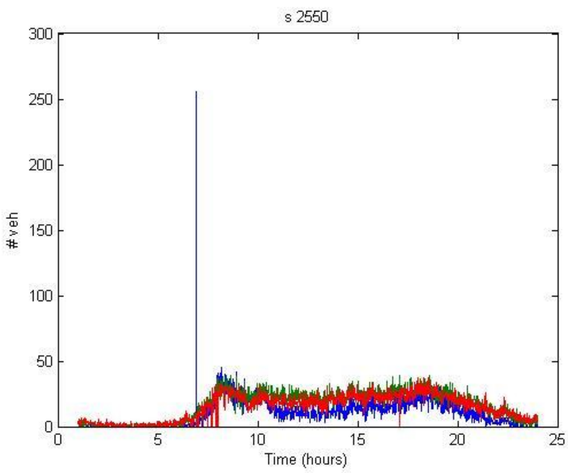


Figure 2a: Vehicle Count Error in 08 ETD

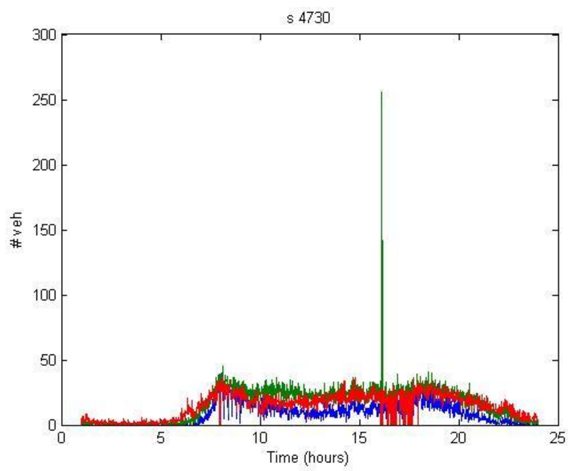


Figure 2b: Vehicle Count Error in 13 ETD

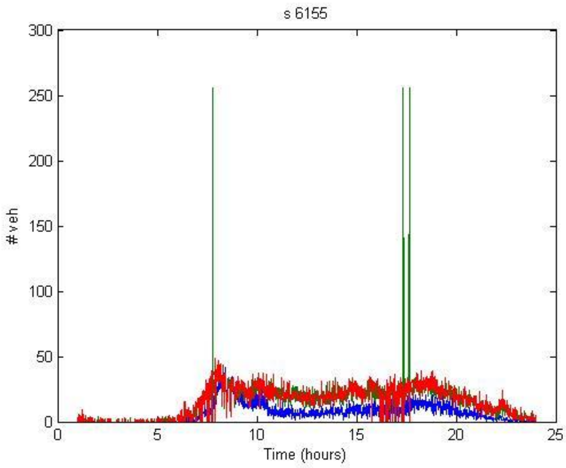


Figure 2c: Vehicle Count Error in 16 ETD

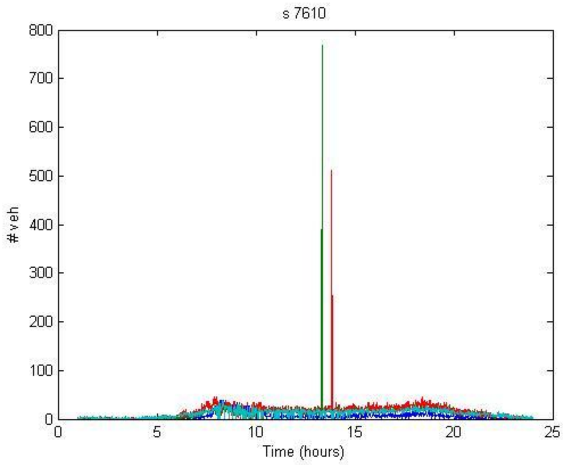


Figure 2d: Vehicle Count Error in 20 ETD

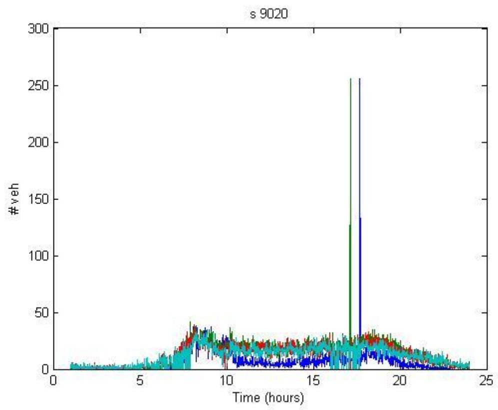


Figure 2e: Vehicle Count Error in 23 ETD

As we said before, each color corresponds to one lane; the blue one is the first lane (the fastest), the green color corresponds to the second lane, the red one corresponds to the third land and the cyan one to the fourth lane. The peaks happened only in one lane (one color) at the same time. The mistaken values (data) for 08ETD, 13ETD, 16ETD and 23ETD are 256 veh/min while in 20ETD the values are much larger. The error has no relation between different loop detectors regarding lanes and times, but it usually happens in the second lane.

In order to fix this error, we merely made the average of the values of one minute before and one minute after. Because this error is always isolated (there are never two mistaken followed minutes). Furthermore, the values next to the mistaken data are correct and we suppose that the traffic conditions do not change drastically within a minute.

Occupancy

The other type of data affected for this error is the occupancy. There is only one loop detector affected and it is 04ETD. This loop detector is one of the four simple LD and one of the most congested in the highway.

We detected this error in the same way that we detected vehicle counting errors. We plotted the data for each loop detector. Afterwards, we noticed that 04ETD occupancy had some errors because the occupancy values over passed 100%.

Figure 3a shows the occupancy data of 04ETD during all the day, where X-axis represents the hours of the day and the Y-axis is the occupancies per lane in minute data. Each color corresponds to one different lane with the same relation we explained before.

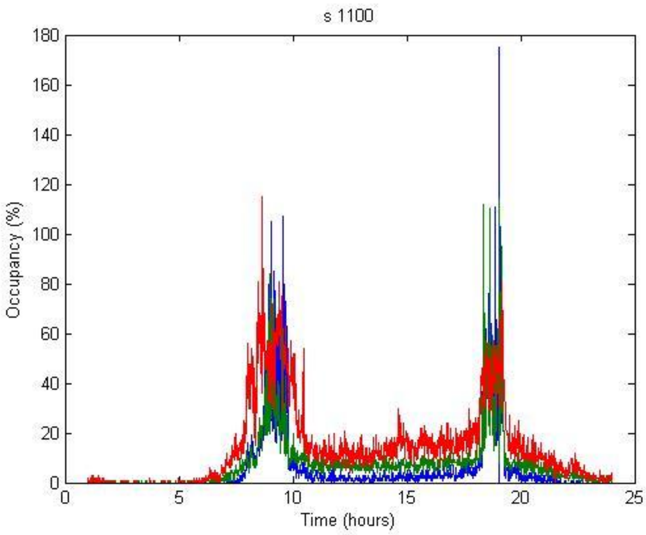


Figure 3a: Occupancy Error in 04 ETD

In order to contrast it with another data, we compared this figure with the plots of the data of the loop detector downstream (03 ETD) and upstream (05 ETD).

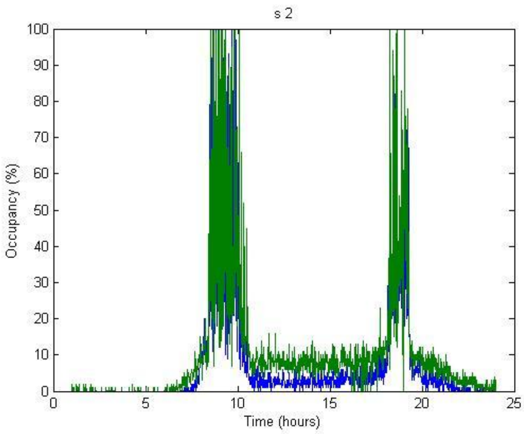


Figure 3b: Occupancy in 03 ETD

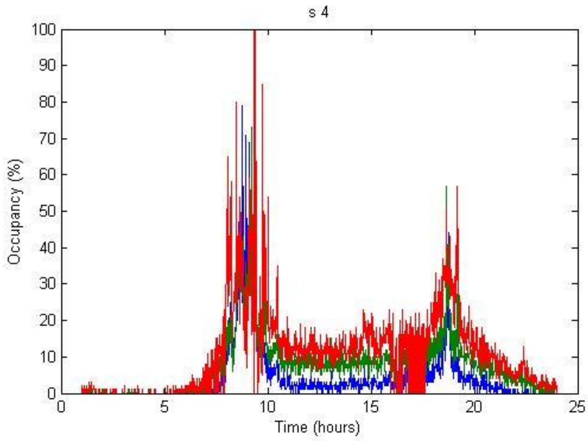


Figure 3c: Occupancy in 05 ETD

Figure 3b and Figure 3c reveal that occupancies are as high as in 04 ETD but they do not overpass 100% occupancy.

We fixed this error changing the wrong values (over 100) by a value of 100.

Zero Error

We noticed this error when plotting the data appeared a lot of fluctuations in the figures and scattered data. That is why we decided to check the data closely.

In some random minutes the loop detector seems not to work and it does not record any information. This phenomenon always occurs in all the lanes at the same time (same minute). We called this type of error Zero Errors.

Moreover, there is no relation between the minutes when this error occurs. But there is a type of relation in the time periods that it happens.

Figure 4 presents the Zero Errors of 17 ETD2; on the left side of the figure there is occupancy data, on the middle we can find the Speeds data and on the right side there are the Vehicle Counts. Each row is a different minute and each column is a different lane. The values are aggregated minute data of the corresponding data type.

hwb23(1, 12).occ <1440x4 double>

	1	2	3	4
472	30	21	25	25
473	15	15	18	14
474	0	0	0	0
475	28	19	51	20
476	0	0	0	0
477	20	17	28	16
478	21	20	44	33
479	0	0	0	0
480	0	0	0	0
481	24	17	23	31
482	100	0	38	15
483	0	0	0	0
484	41	32	19	19
485	14	14	13	9
486	13	16	18	15
487	15	11	39	29
488	9	4	25	17
489	0	0	0	0
490	4	4	18	11
491	0	0	0	0
492	5	3	9	3

hwb23(1, 12).tmean_speed <1440x4 double>

	1	2	3	4
472	27	32	26	26
473	39	39	33	30
474	0	0	0	0
475	29	36	14	19
476	0	0	0	0
477	35	31	26	27
478	31	29	15	19
479	0	0	3	0
480	0	0	0	0
481	26	34	18	15
482	3	0	9	12
483	0	0	0	3
484	23	24	32	32
485	44	46	44	44
486	42	46	42	37
487	43	42	18	23
488	61	52	27	27
489	0	0	3	0
490	65	60	38	44
491	0	0	0	0
492	71	75	76	71

hwb23(1, 12).vol <1440x4 double>

	1	2	3	4
472	25	23	20	20
473	26	23	24	17
474	0	0	0	0
475	24	16	23	14
476	0	0	0	0
477	21	15	25	20
478	22	21	19	21
479	0	0	0	0
480	0	0	0	0
481	19	16	17	14
482	9	0	14	7
483	0	0	0	0
484	24	17	23	22
485	27	22	24	17
486	22	25	26	21
487	21	15	21	21
488	22	9	21	16
489	0	0	0	0
490	13	9	26	19
491	0	0	0	0
492	20	11	23	11

Figure 4: Zero Error Data in 17 ETD02 between minutes 472 and 492

As we can see there is a huge number of zero errors, which in some periods could represent 30-40% of the data. This error is not negligible an affects the analysis of the data. Because of that it is important to fix it before making any analysis.

This type of error, unlike others, affects the three data types and all lanes at the same time. That is why it is more difficult to fix it and we have used sophisticated methodologies.

This problem can be minimized using Moving Averages (See Annex C) but it decreases somehow all the values, making the result under estimated. It also creates unexpected scatter.

We have studied every Loop Detector individually in order to find whether it has Zero Error and in which part of the day (time) appears. The night hours (00h to 05h) are not studied because it could be possible that, during one minute, no vehicles pass in any lane. This fact, is not possible during the day. We classify all loop detectors into four different classes:

I. **Without Zero Error:** 33% of all loop detectors do not have any Zero Error. These loop detectors are: 02ETD, 04ETD, 07ETD, 11ETD, 12 ETD, 19ETD, 24ETD and 28ETD. (Figure 5a)
II. **Zero Error concentrated in one part of the day:** 25% of all LDs have Zero Error concentrated in one part of the day. Almost all between 15:30 and 18:00 (exception of 08ETD). These LDs are: 03ETD, 08ETD, 10ETD, 13ETD, 18ETD and 26ETD. (Figure 5b)

III. **Zero Error concentrated in two parts of the day:** 21% of LDs have two different periods with this error: the first one is in the morning (05:00 to 07:30) and the second one is in the afternoon (same period of class II). The LDs in this class are: 05ETD, 16ETD, 23ETD, 17ETD and 27ETD. (Figure 5c)

IV. **Zero Error during almost all day**. This class is the most problematic because Zero Error happens during a big part of the day. Five LDs are classified in class IV: 17ETD02, 17ETD01, 20ETD, 21ETD and 22ETD. (Figure 5d)

We decided to plot the added Vehicle Counts during the day hours of all lanes in order to find out when this error occurs. Thus, when the dot of the plot is in 0 veh/min means that all lanes have zero vehicle count and the Zero Error happens. While, when there is at least one lane with non-zero value (possible to happen) in the figure will not be displayed as an error because the dot will not be in 0 veh/min. The night hours are not plotted in the following figures because they are not relevant.

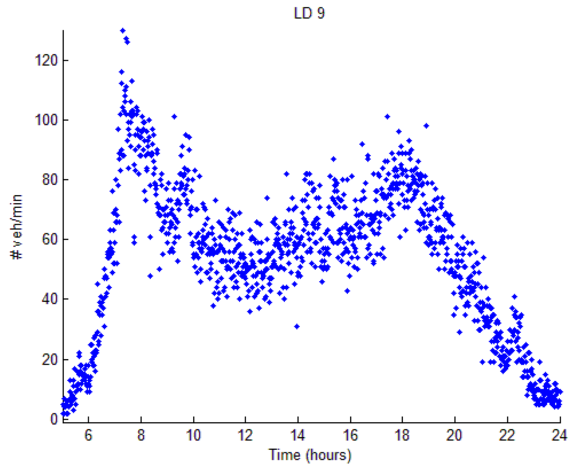


Figure 5a: Vehicle counts in all lanes of 12ETD that shows LDs without Zero Error (Class I)

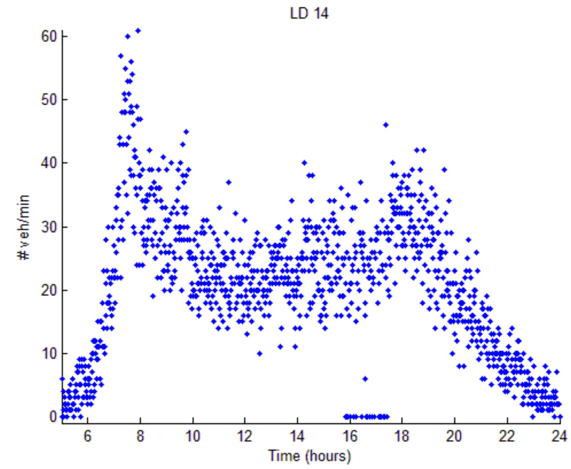


Figure 5b: Vehicle counts in all lanes of 18ETD that shows LDs with Zero Error concentrated in one part of the day (Class II)

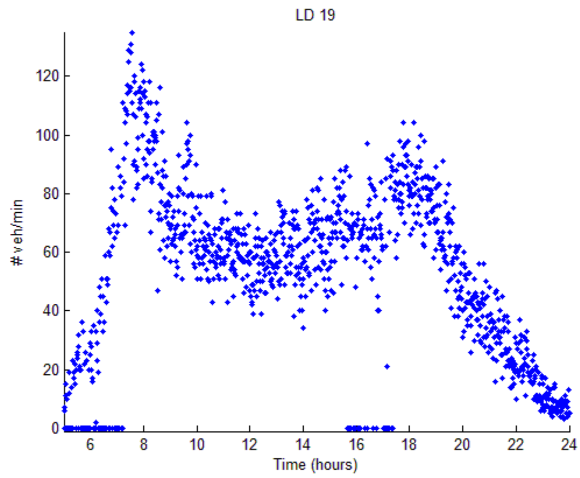


Figure 5c: Vehicle counts in all lanes of 23 ETD that shows LDs with Zero Error concentrated in two parts of the day (Class III)

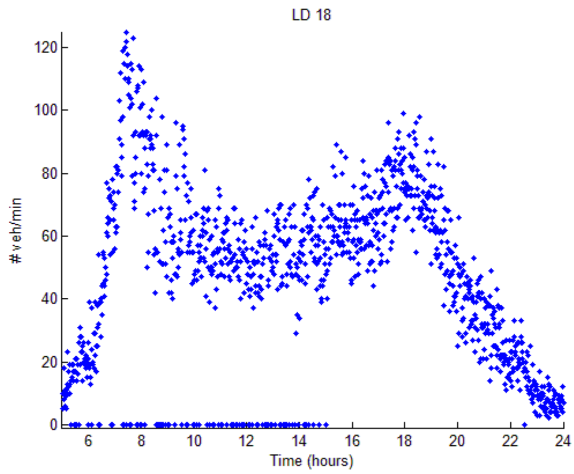


Figure 5d: Vehicle counts in all lanes of 22ETD that shows LDs with Zero Error during almost all day (Class IV)

As we have showed before this type of error affects the three different types of data we have been provided with: vehicle counts, time mean speeds and occupancy; giving a value of zero in the three data types.

First of all we searched the exact minutes when this error occurs. Then, we applied for each minute a fixing procedure (explained below) going forward minute to minute during the day.

Fixing methodology

First, we fixed the vehicle counting data. For each lane we gave the maximum value between the two minutes before and after the studied one. We have done it this way because calculating the average the result shows under estimated values. We think this error could occur when the vehicle counts exceed some threshold, that is why we have chosen using the maximum. We have used only an interval of two minutes because with higher time intervals, e.g. 5 minutes, there is the possibility that it is always using the same maximum value (zero error can appear more often than every 5 minutes). I.e. the maximum value would be dragged during the procedure and it would be always the same.

When vehicle counting data was fixed, we fixed the speed data. The speed usually does not change drastically between one minute and the following one, that is why we chose to use the average of near speeds. We have fixed it making the average of the values of the two previous minutes and the value of the following minute. If the value of the following minute is also mistaken we only took into account the two previous minutes.

To end up we have fixed the occupancy value. We used one relation between the three types of data that could give us a very good approach.

The relation between the three data types is governed by the following formula:

$$k = \frac{Occ}{le} \quad (1)$$

We can rewrite this formula using the following relations $q = \frac{N}{t}$ and $q = v_s \cdot k$, as:

$$\frac{N}{t} = \frac{Occ}{le} v_s \quad (2)$$

Where k is the density *(veh/km),* q the flow *(veh/hour),* N is the number of vehicles that pass through the loop detector during time *t (hours), Occ* is the occupancy of the loop detector in so much per one, le is the effective length *(km)* and v_s is the space mean speed *(km/hour)*.

The main problem of applying this formula is that our speed data are given in time mean speed, and we need space mean speeds. These two types of speeds are related by:

$$v_t = v_s + \frac{{\sigma_s}^2}{v_s} \quad (3)$$

Hence, time mean speed is space mean speed plus standard deviation of space mean speeds divided by space mean speed. This means time mean speed will be always greater than space mean speed.

Rakha and Zhang propose a relationship for estimating space mean speeds from time mean speeds and they demonstrate that only produces an error between 0 to 1 percent.

$$v_s \approx v_T - \frac{{\sigma_T}^2}{v_T} \qquad (4)$$

$${\sigma_T}^2 = Var(v_T) \qquad (5)$$

Where v_T is the time mean speed *(km/hour)* and ${\sigma_T}^2$ is the variance of the time mean speed.

Another problem appears because we do not have individual speeds v_i, so we cannot calculate the $Var(v_T)$ directly.

$$Var(v_T) = \frac{1}{N}\sum_{i=1}^{N}(v_i - v_T)^2 \qquad (6)$$

Metin Çakanyıldırım shows how to compute standard deviations of sample means with unknown individual standards deviations; i.e. it is not necessary to have the individual speeds to calculate the variance of the time mean speed.

Taking into account the parallelism between the sample means $\bar{x}$ and time mean speeds v_T:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad (7)$$

$$v_T = \frac{1}{N}\sum_{i=1}^{N} v_i \qquad (8)$$

We can rewrite the equations in order to calculate the variance of time mean speed:

$$Var\left(v_{T,j}\right) = \frac{1}{m}\sum_{j=1}^{m}(v_{T,j} - \bar{v}_T)^2 \qquad (9)$$

Where j is the index that indicates minute and $\bar{v}_T$ is the mean of time mean speeds during *m* different minutes and can be computed by:

$$\bar{v}_T = \frac{1}{m}\sum_{j=1}^{m} v_{T,j} \qquad (10)$$

Once we had the variance of time mean speeds, we can calculate easily the space mean speeds for each minute with equation (4).

Initially we need the le (effective length) in order to use *relation (2)* and calculate the occupancy value. Effective length is a constant value that can be obtained through probabilistic approach.

First of all, we have to calculate the value that this constant takes in *formula (2)* using the correct data (without Zero Error).

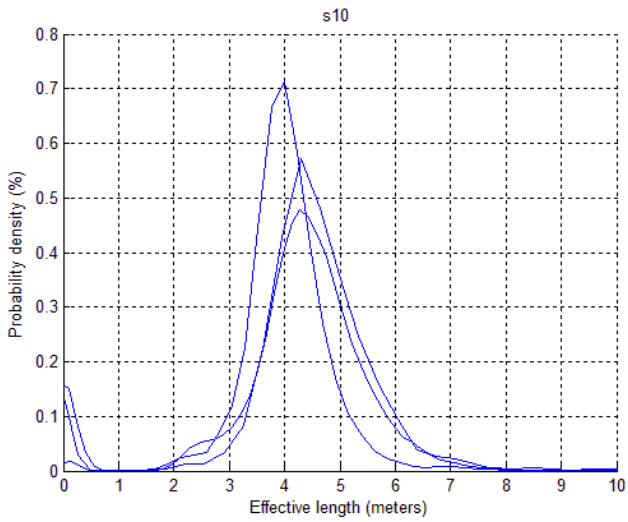


Figure 6: Density of effective lengths of 13ETD

Figure 6 shows the probabilistic density of all the values calculated as effective lengths in 13 ETD.

Each line represents the probabilistic effective length density of one lane. We only need one representative value of all these range of values in order to use it as a constant. As we can see, one representative value for effective length could be the value with higher density, i.e. the mode of the sample. That is why we calculated the mode per section and lane and we used this value as the effective length for that section and lane in order to calculate the Occupancy in the fixing procedure of Zero Error data. Finally we implement the following equation:

$$Occ = \frac{N}{t}\frac{le}{v_s} \qquad (11)$$

All this procedure was repeated for all loop detectors with Zero Error until all LDs were fixed.

Figure 7 shows how fixed data looks like in comparison with Figure 4.

hwb23(1, 12).occ <1440x4 double>

	1	2	3	4
472	30	21	25	25
473	15	15	18	14
474	16	14	25	17
475	28	19	51	20
476	16	15	29	19
477	20	17	28	16
478	21	20	44	33
479	13	16	29	20
480	15	15	34	24
481	24	17	23	31
482	100	0	38	15
483	31	26	30	24
484	41	32	19	19
485	14	14	13	9
486	13	16	18	15
487	15	11	39	29
488	9	4	25	17
489	8	7	23	15
490	4	4	18	11
491	7	5	14	9
492	5	3	9	3

hwb23(1, 12).tmean_speed <1440x4 double>

	1	2	3	4
472	27	32	26	26
473	39	39	33	30
474	32	36	24	25
475	29	36	14	19
476	32	34	21	24
477	35	31	26	27
478	31	29	15	19
479	33	30	21	23
480	30	31	18	19
481	26	34	18	15
482	3	0	9	12
483	17	19	20	20
484	23	24	32	32
485	44	46	44	44
486	42	46	42	37
487	43	42	18	23
488	61	52	27	27
489	56	51	28	31
490	65	60	38	44
491	64	62	47	49
492	71	75	76	71

hwb23(1, 12).vol <1440x4 double>

	1	2	3	4
472	25	23	20	20
473	26	23	24	17
474	26	23	24	20
475	24	16	23	14
476	26	23	25	21
477	21	15	25	20
478	22	21	19	21
479	22	21	25	21
480	22	21	25	21
481	19	16	17	14
482	9	0	14	7
483	27	22	24	22
484	24	17	23	22
485	27	22	24	17
486	22	25	26	21
487	21	15	21	21
488	22	9	21	16
489	22	15	26	21
490	13	9	26	19
491	22	15	26	21
492	20	11	23	11

Figure 7: Zero Error Data Fixed in 17 ETD02 between minutes 472 and 492.

Drift Error

Drift Error appears in real loop detector data (measured) and it consists of counting fewer vehicles than the amount that actually passes through the loop detector. The absolute error grows when more vehicles pass through.

First, we have checked if every loop detector could have Drift Error. In order to check it we have compared through cumulated plots the data of one loop detector with the data of a nearer loop detector, comparing only the part of the day without Zero Errors and also comparing loop detectors without ramps between them. We can find out two different situations in this comparison:

1. The curves in the cumulated plot of different loop detectors are more or less the same during the plotted part of the day. This means that no Drift Error exists in those two loop detectors. (Figure 8)

2. The other situation takes place when one curve is growing faster than the other one. It means the loop detector of the curve in the bottom presents Drift Error and it is always counting fewer vehicles than it should. When Drift Error appears we need one loop detector as a reference in order to fix the other one. We will always take as reference loop detector the one that corresponds to the curve of the top of the plot. (Figure 9)

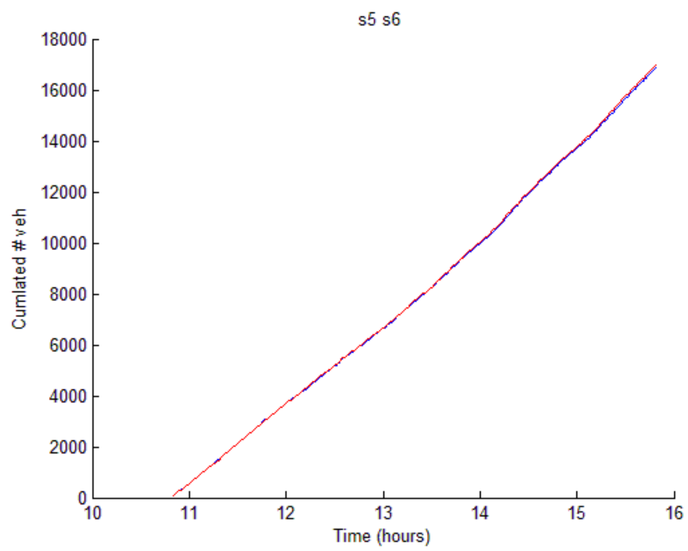


Figure 8: Cumulated Plot of 07ETD and 08ETD with no Drift Error

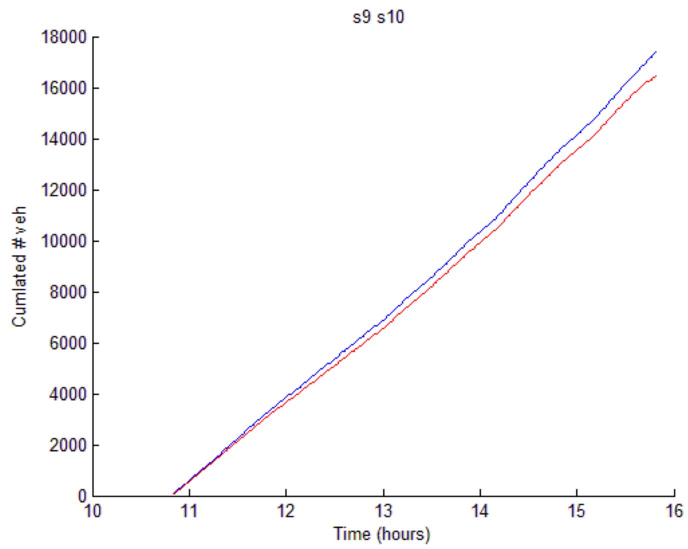


Figure 9 – Cumulated Plot of 12ETD and 13ETD with Drift Error in 13ETD

Once we knew if every single loop detector has Drift Error or not and in which parts of the day the Zero Error appears, we can proceed to fix all the Drifts.

This type of error only affects vehicle counts. As we said previously in order to fix this error we need a reference loop detector, the LD we think that has better quality data, i.e. without Drift Error. We have already fixed the Zero Error before fixing Drift Error. Fixed zero error data are considered as good data.

First of all, we plotted in the same figure two cumulative plots of different loop detectors. The topper curve would be the reference data (supposedly without Drift Error).

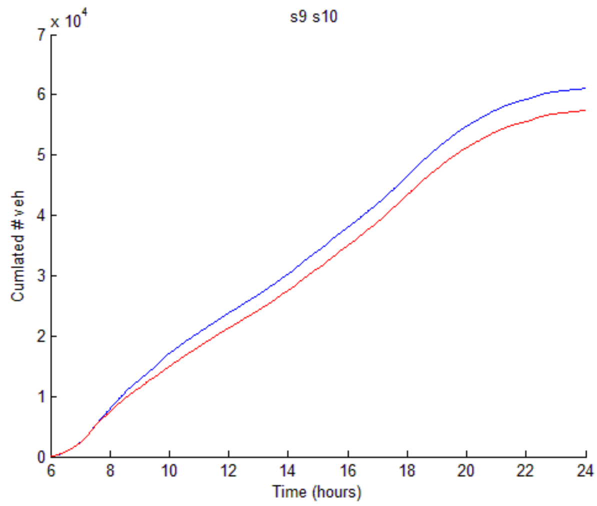


Figure 10: Cumulated Plot of 12ETD and 13ETD during all day

Figure 10 shows that the difference between the two lines is growing during the day due to Drift Error. To fix this error we need a sufficient long period of time in order to count the cumulated number of vehicles that have passed through every loop detector. We named this period of time *T*.

We define the cumulated number of vehicles $N_{i,T}$ that have passed through one loop detector i during time T as the sum of the vehicles counted every minute in that loop detector $n_{i,t}$ during time T.

$$N_{i,T} = \sum_{T} n_{i,t} \qquad (12)$$

The correction factor ε can be defined as the quotient between the cumulated vehicles of the mistaken detector and the cumulated vehicles of the reference loop detector during the same period of time.

$$\varepsilon_i = \frac{N_{i,T}}{N_{Ref\,i,T}} \qquad (13)$$

For the same loop detector there could be more than one correction factor. It depends on how many different Drift Error patterns could be distinguish during the day, e.g. during the morning and the afternoon.

Finally, we have applied the following equation for each minute in the period of time we wanted to fix. This time has not to be in the same period of time when correction factor is calculated.

$$\tilde{n}_{i,t} = \frac{1}{\varepsilon_i} n_{i,t} \qquad (14)$$

Where $\tilde{n}_{i,t}$ is the corrected vehicle count.

It is important to remark that the period of time when the correction factor is calculated, it has to begin and end in non-congested times. Otherwise the difference between cumulated number of vehicles would be not only due to the Drift Error but rather the number of congested cars plus the Drift Error.

Figure 11 reveals how fixed data looks like.

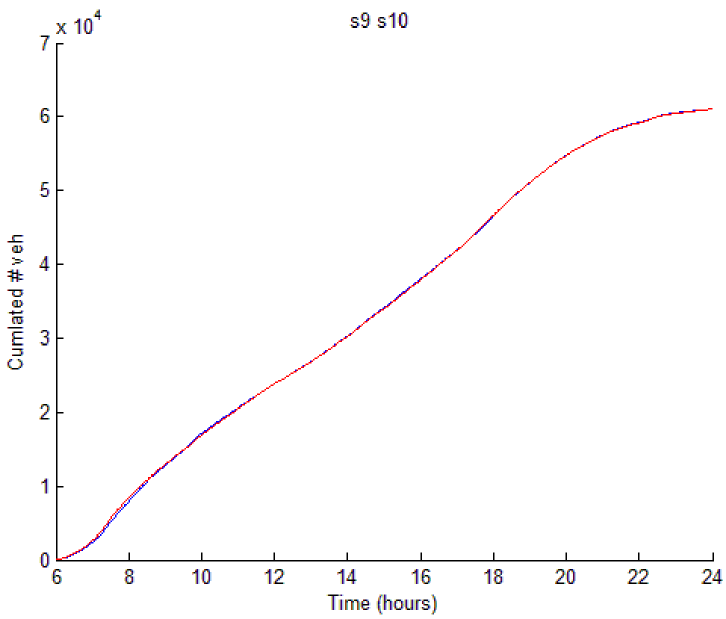


Figure 11: Cumulated Plot of 12ETD and 13ETD with Drift Error fixed

Procedure to fix Errors

First of all, we fixed all the peaks errors explained in the first part of this section. Afterwards, we managed to calculate drift correction factors in periods of time without zero error. We calculate these factors in order to apply it after, in longer periods that could be affected by zero errors.

Once we had these factors, we fixed all the zero errors with the procedure explained in "Zero Error" part.

The next step is correcting the drift errors. We used the correcting factors calculated before but now applying it in longer periods of time. This way, we are using the data without any errors as a reference to correct all the data. On the other hand, if we calculated drift correction factors after fixing zero error, we could use the corrected zero data as a reference.

Data Sets

We generated three different data sets based on the original data provided by "Servei Català de Trànsit". But only one is used for almost all Thesis. The real naming of these data sets is displayed in "E" section of this annex.

1. The first data set is the same original data but only with the file structure changed. This change is in order to be able to program and make the analysis of the data easier. All the other data sets will have the same file structure of this one.

2. The second data set differs from the previous one only for the data that contains zero error. Now, this data is fixed.

3. The third data set has zero error fixed and the drift error fixed.

C. Tools used

We have used a lot of different tools in order to explain in the best possible way the behavior of the traffic and the results and conclusions we have found. In this section of the Annex the different tools are explained; how they are build; which data are used in each one and for which purpose they are used.

Contour Plot

The Contour Plot in Traffic is a tool that shows us how the whole highway or section during one period of time is behaving. Moreover, it gives us a global view of what is happening, i.e. when and where congestion appears, the length of the queues, rush hours and most problematic parts of the highway.

Contour Plot is a Space –Time map illustrated with different colors, where each color corresponds to a range of values of one traffic variable. It could also been plotted in 3D (Figure 11), where X-axis is the time, Y-axis is the space and Z-axis is the traffic variable that we want to show and it gives the color.

This type of graphs can be built with speeds or occupancies. The most used are Speed Contour Plots. But in our study, we preferred to use occupancies because 20% of Loop Detectors are simple, i.e. these Loop Detectors do not get speeds. That is why we decided to use Occupancy Contour Plot cause of data could reach more locations and the graph will be more completed and representative.

The data used in this graphs are the aggregated occupancies per lane (averaged per location) of all loop detectors between the minutes corresponding to 7:00 and 20:00. We chose this period of time because it is when all the interesting things happen. During the night hours and after 20:00 nothing important takes place.

The section of the highway that appears in the graph corresponds to the space between the first loop detector (PK 0,37) and the last one (PK 11,20). Each LD data are set in the Kilometric Point where their loop detector is located. The data between loop detectors are interpolated in a linear way.

The graduation of the colors, that represent the occupancy, is growing from blue (0% Occupancy) to brown (100% Occupancy), how you can see in the Figure 11 and Figure 12.

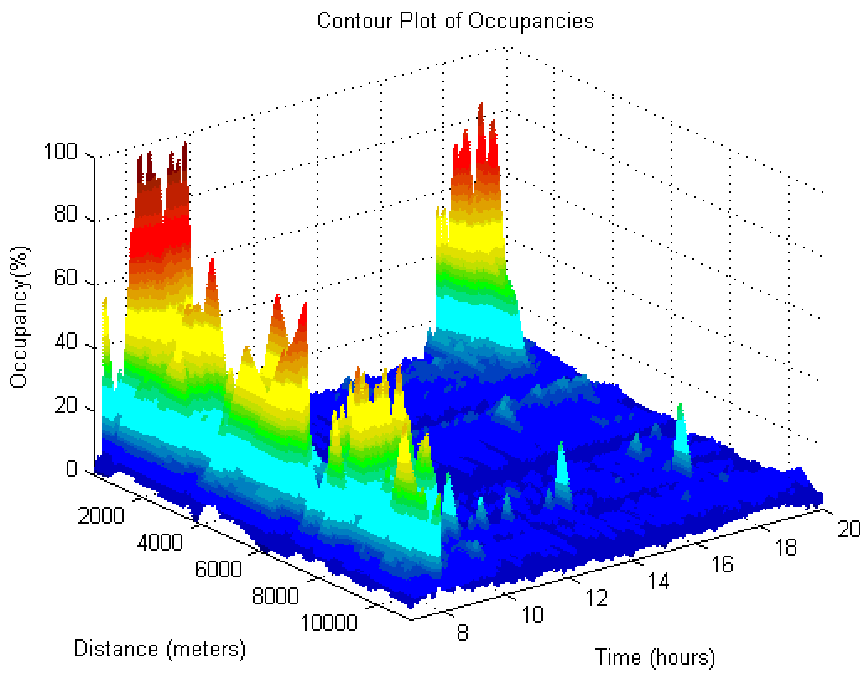


Figure 11 : 3D Contour Plot

The normal Contour Plot (2D) gives the same information of 3D Contour Plot but without the third dimension that is implicit in the color of the graph. Moreover, normal Contour Plots (Figure 12) are better to see exact times and locations.

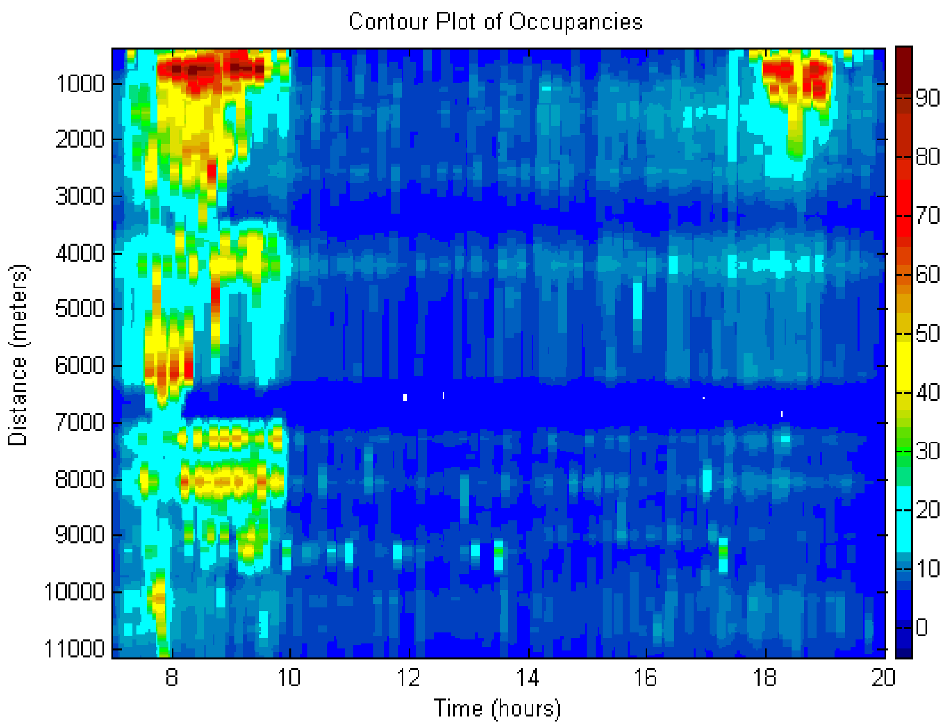


Figure 12: Contour Plot between 7h and 20h

Total Flow or Demand Diagrams

In this type of diagrams you can see the total flow during a given period of time through different locations. It gives a global view of the flow through the highway. We also consider this diagram important to understand how the highway works and the importance of the Off/On Ramps in each part of the highway.

We called them Demand Diagrams because if we take into account a big period of time, the total flow during this period of time will correspond to the demand. This is due to the fact that all the vehicles that wanted to pass through the highway have already passed and no vehicle is stuck there.

In order to plot this diagram we added all the flows (vehicle counts) of all lanes during a fix period of time. This is done for each loop detector. Afterwards, it is plotted in each LD location.

X-axis reveals the traffic direction, where right is going downstream and left upstream. The axis number only indicates the LD number, i.e. X-axis is not a real space axis. Y-axis indicates the added flow in each location during the fixed period of time.

When the line in the figure goes up, it means that there is at least one on ramp between them. If on the other hand, the line goes down, it means there is at least one off ramp. If the line goes up or down without any ramp between the loop detectors is due to a Data Error.

In order to have a perfect view of how Traffic moves in the Ramps we complemented it with the scheme of the highway. Figure 13 shows where each LD is and the location of the ramps.

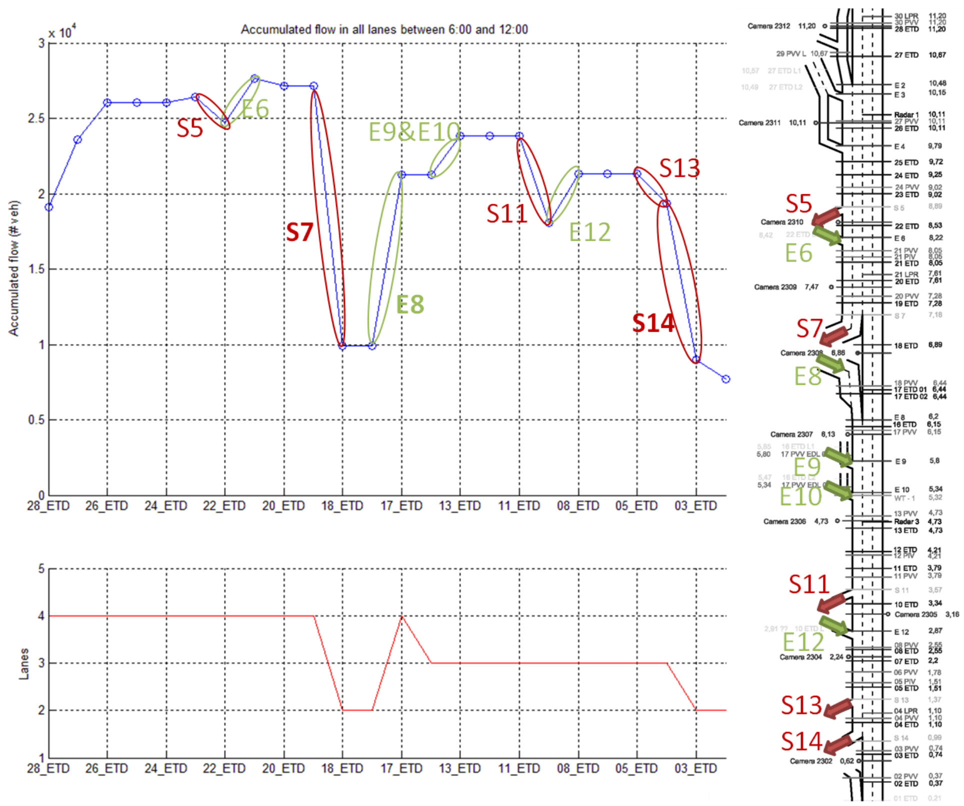


Figure 13: Flow in all lanes between 6:00 and 12:20

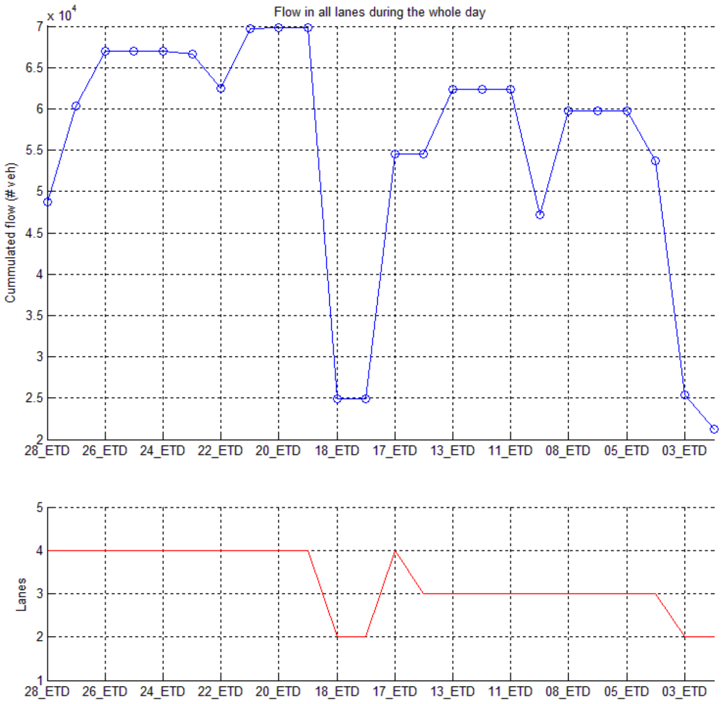


Figure 14: Total demand during the entire day

Demand Diagrams could also be useful to check if the traffic behaves in the same way in different parts of the day regarding ramps utilization. Are Ramps used in the same way in the morning and in the afternoon?

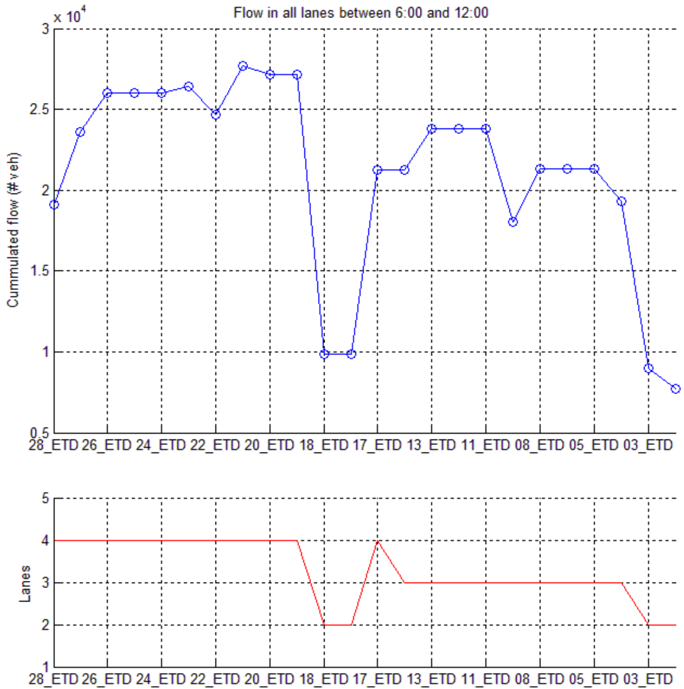


Figure 15: Total flow in the morning hours (6:00-12:00)

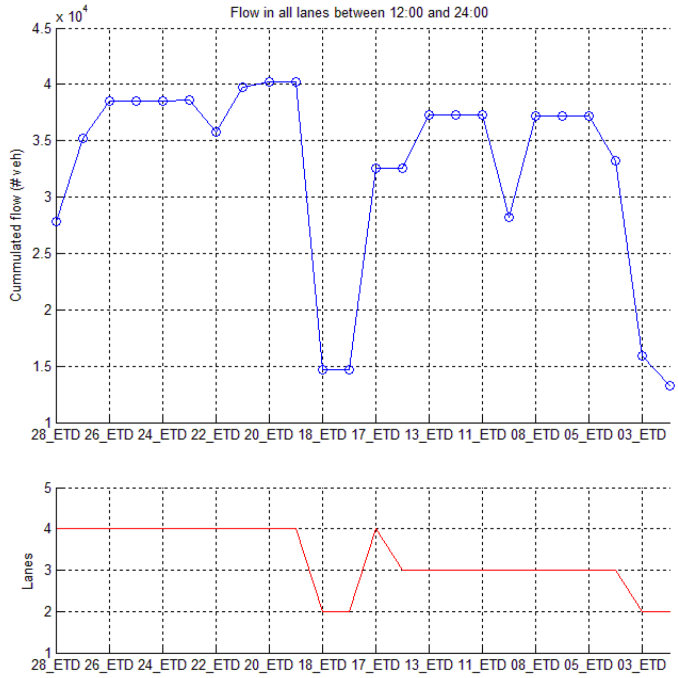


Figure 16: Total flow in the afternoon/night (12:00-24:00)

We can ensure that the behavior of the ramps is more or less the same throughout the day. The only significant difference is the change in the behavior of the on ramp between 08ETD and 10ETD. Comparing it with the other ramps, it has less use in the morning than in the afternoon-night.

Moving Averages

We have used this tool in order to reduce the scatter in the plots, especially when the data of each minute are plotted one by one. This tool reduces the non-sense fluctuations between the following minutes that makes the analysis of the plots very difficult. With this tool the plots are smoother and they follow the real traffic fluctuations.

Moving Averages also called rolling or running averages consist on using a set of data points creating series of averages of subsets of the full data. i.e. modifying the value of one traffic variable (e.g. occupancy, speeds or vehicle counts) for the average of one range of values around them, and making the same for all the values in one set of data points (vector). Where each data value of the set corresponds to one different time (minute).

We have tried different range of times (e.g. 3, 5, 7, 9 minutes). But we applied for all the plots a 5 minutes range because the changes are not very visible. We are also trying to optimize the number of mathematical operations as much as we can.

We have programmed in Matlab one function in order to operate Moving Averages easily. The input of this function is one vector that you want to 'average' and the output is a vector with the same length and with the moving averages already implemented.

Figure 17a and Figure 17b show the real and visual differences between using Moving Averages and not using it. Figures represent the aggregated minute data of time mean speeds of 05ETD in lane 1 between 12:00 and 18:00. We have used this tool in almost all the plots of the Thesis.

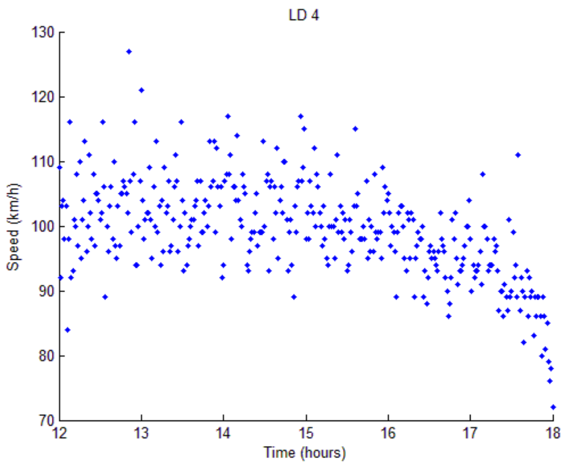


Figure 17a: Without Moving Averages

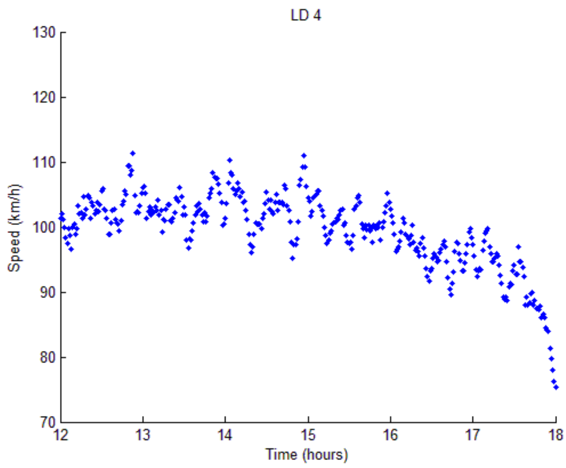


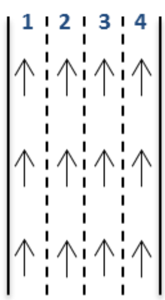
Figure 17b: With Moving Averages

Subplots of the 3 data types

The figures explained in this section consist on three subplots. I.e. three small plots, where each small plot represent one of the traffic variable we have data from (time mean speeds, vehicle counts and occupancies). Moreover, the data of all the lanes are plotted individually (a different color per lane). They are very useful to compare the different traffic data types in identical periods of time. Furthermore, the Speed Plot has the Variable Speed Limit data plotted as a curve in pink color.

The relation between colors and lanes is the following one:

Lanes	Color
1st	Blue
2nd	Green
3rd	Red
4th	Cyan Blue



The lanes doesn't exist in all loop detectors, that is why in some occasions there are only two, three or four different colors in the subplots.

These plots are built with moving averages and using the aggregated data per minute provided. Each plot represents throughout a variable period of time (X-axes) the evolution of one traffic variable data (Y-axes). In the top of each figure we can find the Occupancy Plot, below them the Flow or Vehicle Counts Plot and in the bottom part the Time Mean Speed Plot. The X-axe is always within the same period of time in the three subplots in order to be able to compare at the same time different data types.

As we said, the data plotted is aggregated data per minute. This means the Y-axis of the Flow Plot is in vehicles per minute not in vehicles per hour.

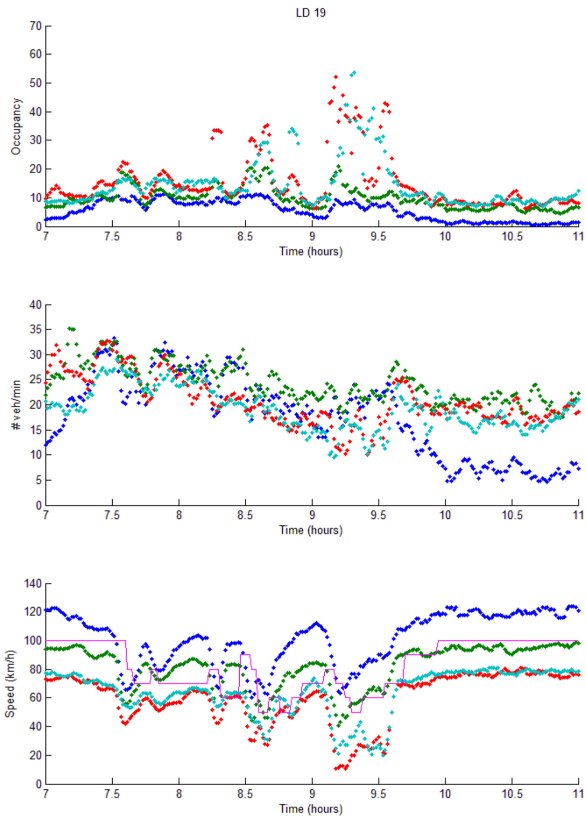


Figure 18a: Subplot of 23ETD between 7:00 and 11:00

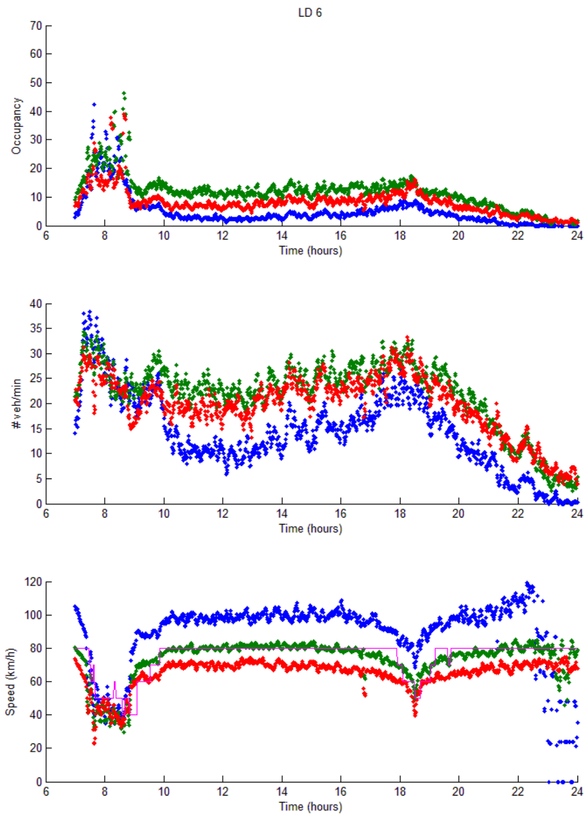


Figure 18b: Subplot of 08ETD between 7:00 and 24:00

Annex D has a collection of all the subplots in all loop detectors.

Fundamental Diagrams

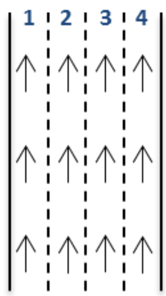
A Fundamental Diagram is one of the most important tools in traffic. They could give us a lot of information about the location we are studying.

In order to build the Fundamental diagrams, we used the aggregated data per minute and lane of vehicle counts and occupancies data sets. We have not used densities because we were not directly provided of this type of data. If we had used densities, we would have had to calculate them and we would have accumulated errors that would distort the Diagrams and the conclusions. That is why we decided to use occupancies instead of densities.

In the X-axis there is the occupancy as a percentage and in the Y-axis there is the flow as vehicles per hour for each lane. Each point in the FD figure corresponds to the aggregated data per minute, i.e. to calculate the flows in veh/hour we had to multiply the vehicle counts by 60.

Figure 19 presents one Fundamental Diagram, where each color corresponds to one lane.

Lanes	Color
1st	Blue
2nd	Green
3rd	Red
4th	Cyan Blue



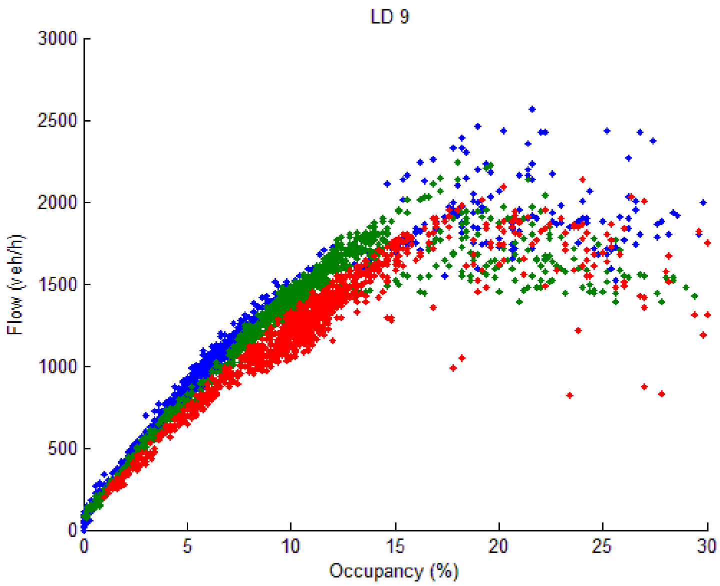


Figure 19: Fundamental Diagram per lane of 12ETD

Figure 19 shows that the behavior of the traffic is very similar in the three lanes, the capacity is around 2000-2500 veh/hour per lane and critical occupancy is around 15% in the three lanes. The middle lane, lane 1 (blue) is the fastest lane because it has the greatest slope. Additionally, lane 2 (green) is faster than lane 3 (red) because the slope is greater.

Fundamental Diagrams can show us many traffic characteristics of the location we are studying. The three more important are the free flow speed, capacity and critical occupancies. We began calculating the last two.

The capacity is the maximum flow that can pass through one location. It is important to determine the capacity in the following scenario: when congestion appears upwards the location and there is no congestion downwards. This scenario is not always fulfilled in our loop detectors locations. That is why only in some specific LDs and lanes we can define the maximum flow measured as the capacity. When the Fundamental Diagram has a nice shape and it represents all the states (Congested, Critical and Uncongested) we can ensure that the capacity is the maximum flow measured. The main problem of our Data is the lack of congested state data.

Critical occupancy is closely correlated with capacities, because capacity is the flow of the critical point and critical occupancy is the occupancy of the critical point. For critical point we understand the point that uncongested state changes to congested state and vice versa. Table 1 shows the maximum flows measured in the different loop detectors and lanes.

Table 1: Maximum flows measured (veh/h per lane)

	Lane 1	Lane 2	Lane 3	Lane 4
02 ETD	900	900		
03 ETD	900	1200		
04 ETD	900	1200	2000	
05 ETD	1500	1500	2100	
07 ETD	1600	1600	1600	
08 ETD	1400	1800	1700	
10 ETD	1800	1500	1000	
11 ETD	1700	1700	1700	
12 ETD	1500	1700	1700	
13 ETD	1500	1700	1600	
16 ETD	1500	1600	1700	
17 ETD 01	1200	1200	1200	1200
17 ETD 02	900	1100		
18 ETD	1200	1200		
19 ETD	1400	1200	2100	1200
20 ETD	1500	1400	1500	1100
21 ETD	1500	1500	1700	1400
22 ETD	1500	1500	1500	900
23 ETD	1700	1500	1500	1300
25 ETD	1500	1500	1400	1200
26 ETD	1500	1500	1300	1300
27 ETD	1500	1700	1300	900
28 ETD	1400	1600	1300	200

The free flow speed is an important traffic variable that shows the average speed of the vehicles moving in uncongested state, i.e. the speed the drivers can drive without any congestion disruption. This speed tends to be different within lanes in the same location. They should differ gradually, being the first lane with greater speeds.

The speed of one state in the Fundamental Diagram corresponds to the slope of the line that connects the origin with the state point in the Diagram. In the case of Occupancy –FD, the slope does not correspond directly to the speed. That is why in our case we have used another methodology in order to find the free flow speeds.

We have collected the data time mean speeds of all the minutes with occupancies lower than the Critical Occupancy, i.e. all the data of uncongested state. If we are not sure of the Critical Occupancy value of one loop detector we have collected the data that we are sure is in uncongested state.

With the collected data speeds we build the probabilistic density distribution of the speeds rounding them to multiple of 2 (Figure 20). In this plot aggregated data of all lanes are used but we can also plot it for disaggregated lane data.

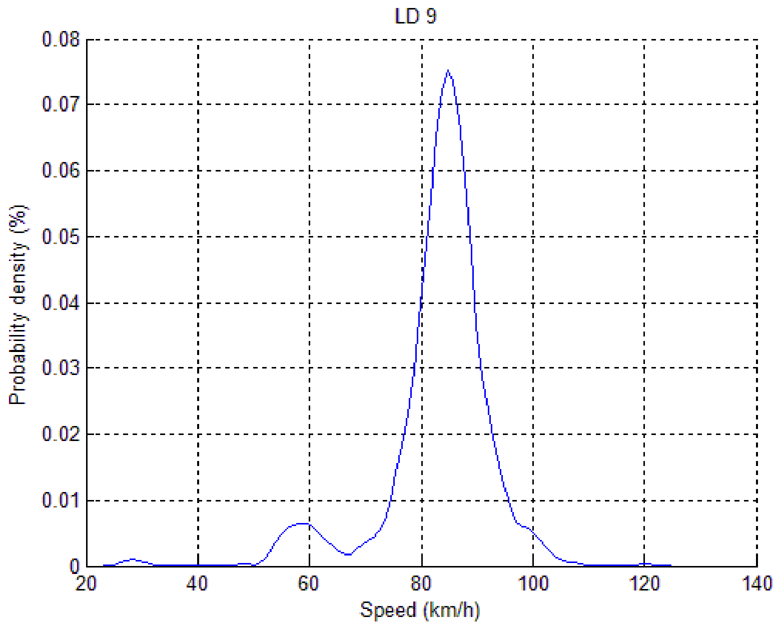


Figure 20: Speed density distribution of all lanes in uncongested state of loop detector 12ETD

We took as free flow speed the speed with higher density, i.e. the mode of the sample. E.g. in 12ETD (Figure 20) corresponds to a free flow speed of 84 km/h.

Following the same methodology for all loop detectors and also doing it individually per lane: we were able to calculate all the free flow speeds (Table 2). Each row corresponds to one different loop detector (location) and the columns are the different lanes. The right column shows the average free flow speed calculated with all aggregated lane data. If there is a gap in one column, it means that that particular lane (lane that corresponds to the column) does not exist in that LD.

Free Flow Speed (km/h)

	Lane 1	Lane 2	Lane 3	Lane 4	Mean per LD	Speed Limit
02 ETD	68	56			62	50
03 ETD	84	74			78	60
05 ETD	100	86	80		88	80
08 ETD	98	82	70		82	80
10 ETD	100	86	82		90	80
11 ETD	74	84	74		78	80
12 ETD	94	84	76		84	80
13 ETD	90	72	82		80	80
16 ETD	102	92	88		96	80
17 ETD	84	84	94	78	86	80
18 ETD	108	102			106	100
19 ETD	110	94	98	90	98	100
20 ETD	112	98	96	90	98	100
21 ETD	116	100	96	88	100	100
22 ETD	110	102	98	94	102	100
23 ETD	120	94	74	80	92	100
25 ETD	116	102	98	94	102	100
26 ETD	112	104	96	90	100	100
27 ETD	118	104	94	80	98	100

Table 2: Free flow speeds per lane and average for all lanes

Travel Time Index

We have used this Index in order to show somehow the delays that drivers suffer caused by congestion. This index provides us the extra time each vehicle need to pass through one area in congested periods. Moreover, it is independent of the distance traveled.

Travel time index compares the travel time between one studied time and the travel time in no congestion state. In mathematical terms it can be calculated as: the free flow speed divided by the speed in one studied time (usually speed in congestion states).

Thus, we can define travel time index with the following equation:

$$TTI = \frac{v_f}{v_i}$$

Where, v_f is the free flow speed (*km/h)* and v_i is the speed in the studied time (*km/h)*.

We calculated the travel time index every 15 minutes in the morning rush hour for all the loop detectors that have speed data. It is calculated for all the lanes in each LD and the average of all lanes is also calculated. In the afternoon rush hour (17:30 – 19:00) it is calculated every 30 minutes because the congestion is less important.

Morning rush hour travel time indexes (7:30-10:00):

Table 3a: Travel Time Indexes at 7:30

	Lane 1	Lane 2	Lane 3	Lane 4	Average
02ETD	1.78	1.47			1.63
03ETD	1.35	1.28			1.3
05ETD	1.48	1.53	1.89		1.59
08ETD	1.36	1.4	1.34		1.35
10ETD	1.25	1.17	1.11		1.19
11ETD	1.46	1.35	1.32		1.38
12ETD	1.67	1.58	1.51		1.58
13ETD	1.4	1.45	1.51		1.43
16ETD	1.15	1.18	1.24		1.21
17ETD1	1.13	1.04	1.12	1.03	1.09
18ETD	1.14	1.1			1.13
19ETD	1.25	1.17	2.19	1.92	1.51
20ETD	1.29	1.29	1.66	1.72	1.43
21ETD	1.39	1.5	2.67	2.16	1.76
22ETD	1.16	1.12	1.11	1.11	1.14
23ETD	1.15	1.05	1.11	1.17	1.12
25ETD	1.12	1.09	1.13	1.11	1.11
26ETD	1.11	1.11	1.12	1.12	1.11
27ETD	1.14	1.12	1.08	1.16	1.11

Table 3b: Travel Time Indexes at 7:45

	Lane 1	Lane 2	Lane 3	Lane 4	Average
02ETD	3.06	2.26			2.64
03ETD	1.7	1.5			1.58
05ETD	1.44	1.35	1.62		1.45
08ETD	1.78	1.8	1.58		1.7
10ETD	2.27	1.74	1.47		1.81
11ETD	1.6	1.37	1.25		1.4
12ETD	1.87	1.81	1.64		1.76
13ETD	2.06	2.05	2.25		2.08
16ETD	2.5	2.64	2.88		2.71
17ETD1	2.31	2.1	3.03	2.6	2.5
18ETD	1.72	1.61			1.68
19ETD	1.49	1.35	2.09	1.9	1.65
20ETD	1.37	1.35	1.95	1.79	1.54
21ETD	1.33	1.35	1.53	1.54	1.42
22ETD	1.18	1.17	1.13	1.15	1.17
23ETD	1.23	1.12	1.24	1.27	1.21
25ETD	5.09	3.95	3.29	3.76	3.95
26ETD	3.89	3.91	3.56	3.44	3.68
27ETD	1.37	1.35	1.32	1.32	1.33

Table 3c: Travel Time Indexes at 8:00					
	Lane 1	Lane 2	Lane 3	Lane 4	Average
02ETD	2.52	2.03			2.27
03ETD	3.41	3.19			3.26
05ETD	3.11	3.61	4.04		3.48
08ETD	2.5	2.23	1.6		2.05
10ETD	1.35	1.24	1.13		1.25
11ETD	1.48	1.29	1.25		1.34
12ETD	1.38	1.35	1.36		1.35
13ETD	1.54	1.49	1.59		1.52
16ETD	5.26	4.69	5.87		5.33
17ETD1	3.41	3.39	5.8	4.43	4.13
18ETD	1.46	1.4			1.44
19ETD	1.34	1.32	2.03	1.78	1.56
20ETD	1.4	1.44	2.03	1.89	1.61
21ETD	1.32	1.34	1.38	1.32	1.34
22ETD	1.2	1.23	1.23	1.14	1.21
23ETD	1.26	1.14	1.3	1.25	1.23
25ETD	1.29	1.25	1.25	1.27	1.26
26ETD	1.24	1.35	1.32	1.23	1.27
27ETD	1.22	1.2	1.22	1.08	1.17

Table 3d: Travel Time Indexes at 8:15					
	Lane 1	Lane 2	Lane 3	Lane 4	Average
02ETD	2.86	1.99			2.38
03ETD	3.53	3.66			3.55
05ETD	2.53	2.16	2.09		2.24
08ETD	2.21	1.99	1.84		1.99
10ETD	1.93	1.5	1.24		1.54
11ETD	1.59	1.38	1.28		1.42
12ETD	1.43	1.35	1.28		1.35
13ETD	1.78	1.61	1.73		1.68
16ETD	2.54	2.66	2.44		2.6
17ETD1	1.2	1.25	1.18	1.1	1.19
18ETD	1.17	1.14			1.17
19ETD	1.33	1.14	2.09	1.85	1.5
20ETD	1.48	1.5	2.35	2.28	1.77
21ETD	1.85	1.87	3.04	3.36	2.3
22ETD	2.17	2.06	2.8	3.05	2.45
23ETD	1.44	1.42	1.43	1.34	1.41
25ETD	1.16	1.12	1.08	1.08	1.1
26ETD	1.15	1.16	1.09	1.07	1.11
27ETD	1.15	1.12	1.07	1.01	1.08

Table 3e: Travel Time Indexes at 8:30					
	Lane 1	Lane 2	Lane 3	Lane 4	Average
02ETD	2.6	1.59			2.02
03ETD	3.18	2.82			2.97
05ETD	3.91	3.31	3.28		3.47
08ETD	2.22	2.27	1.99		2.13
10ETD	2.5	1.69	1.39		1.8
11ETD	2.03	1.79	1.6		1.81
12ETD	1.43	1.51	1.92		1.57
13ETD	1.46	1.51	1.56		1.48
16ETD	1.11	1.06	1.08		1.11
17ETD1	1.06	1.07	1.06	1.01	1.06
18ETD	1.08	1.06			1.08
19ETD	1.25	1.23	2.31	2.16	1.58
20ETD	1.4	1.52	1.93	2.11	1.66
21ETD	1.81	2.3	3.72	3.86	2.56
22ETD	1.91	2.13	3.53	5.47	2.71
23ETD	1.48	1.46	1.5	1.33	1.44
25ETD	1.18	1.14	1.11	1.15	1.14
26ETD	1.15	1.14	1.14	1.08	1.12
27ETD	1.14	1.11	1.1	1.04	1.09

Table 3f: Travel Time Indexes at 8:45					
	Lane 1	Lane 2	Lane 3	Lane 4	Average
02ETD	3.18	1.9			2.44
03ETD	3.96	4.4			4.11
05ETD	2.39	2.83	5.56		3.05
08ETD	1.76	1.76	1.43		1.63
10ETD	1.3	1.19	1.07		1.2
11ETD	1.51	1.49	2.61		1.75
12ETD	1.59	1.94	2.79		1.94
13ETD	1.87	2.14	2.25		2.03
16ETD	1.14	1.14	1.13		1.16
17ETD1	1.03	1	1.07	1.06	1.05
18ETD	1.13	1.1			1.12
19ETD	1.35	1.34	3.6	3.02	1.88
20ETD	1.62	1.79	2.77	2.73	2.05
21ETD	2.07	2.49	5.16	4.94	3.02
22ETD	1.99	2.11	2.68	3.79	2.47
23ETD	1.36	1.42	1.49	1.32	1.39
25ETD	1.14	1.16	1.15	1.15	1.14
26ETD	1.15	1.21	1.16	1.13	1.15
27ETD	1.17	1.18	1.13	1.03	1.12

Table 3g: Travel Time Indexes at 9:00

	Lane 1	Lane 2	Lane 3	Lane 4	Average
02ETD	3.12	1.66			2.23
03ETD	4.08	4.81			4.33
05ETD	1.55	1.7	2.07		1.72
08ETD	1.22	1.33	1.17		1.22
10ETD	1.27	1.15	1.09		1.18
11ETD	1.53	1.57	3.36		1.89
12ETD	1.45	1.71	3.42		1.85
13ETD	1.29	1.31	1.27		1.27
16ETD	1.09	1.08	1.09		1.11
17ETD1	1.01	1.01	1.13	1.03	1.06
18ETD	1.11	1.09			1.11
19ETD	1.4	1.34	3.53	3.15	1.91
20ETD	1.66	2.33	4.44	5.06	2.63
21ETD	1.82	2.11	5.45	5.18	2.74
22ETD	1.15	1.28	1.39	1.6	1.34
23ETD	1.09	1.12	1.18	1.12	1.12
25ETD	1.11	1.08	1.09	1.08	1.08
26ETD	1.06	1.14	1.1	1.01	1.07
27ETD	1.04	1.08	1.07	0.99	1.04

Table 3h: Travel Time Indexes at 9:15

	Lane 1	Lane 2	Lane 3	Lane 4	Average
02ETD	2.86	2.04			2.42
03ETD	4.52	3.89			4.15
05ETD	1.42	1.76	3.17		1.83
08ETD	1.13	1.18	1.09		1.12
10ETD	1.18	1.13	1.06		1.13
11ETD	1.75	1.83	4.16		2.2
12ETD	1.63	1.89	3.25		2.01
13ETD	1.36	1.38	1.37		1.35
16ETD	1.05	1.13	1.13		1.12
17ETD1	1.07	1.05	1.12	1.09	1.09
18ETD	1.12	1.09			1.11
19ETD	1.28	1.24	2.29	2.09	1.58
20ETD	1.44	1.46	1.76	2.25	1.64
21ETD	1.64	1.92	2.71	3.21	2.16
22ETD	1.74	1.92	5.27	4.9	2.65
23ETD	1.78	2.03	7.12	2.96	2.43
25ETD	1.26	1.32	1.48	1.72	1.41
26ETD	1.1	1.15	1.15	1.14	1.13
27ETD	1.06	1.09	1.08	1.03	1.06

Table 3i: Travel Time Indexes at 9:30

	Lane 1	Lane 2	Lane 3	Lane 4	Average
02ETD	2.28	1.58			1.9
03ETD	1.94	1.26			1.53
05ETD	1.15	1.16	1.22		1.16
08ETD	1.13	1.17	1.18		1.14
10ETD	1.21	1.13	1.1		1.16
11ETD	1.56	1.53	2.62		1.79
12ETD	1.73	1.96	2.28		1.93
13ETD	1.91	2.12	2.09		2
16ETD	1.01	1.09	1.16		1.1
17ETD1	1.09	1.09	1.2	1.13	1.14
18ETD	1.11	1.1			1.12
19ETD	1.33	1.26	2.51	2.26	1.66
20ETD	1.49	1.45	2.1	2.31	1.72
21ETD	1.7	1.86	3.93	3.79	2.36
22ETD	1.54	1.58	4.08	6.35	2.33
23ETD	1.33	1.4	2.26	2.92	1.69
25ETD	1.15	1.18	1.17	1.16	1.16
26ETD	1.09	1.2	1.13	1.12	1.13
27ETD	1.07	1.13	1.09	1.09	1.08

Table 3j: Travel Time Indexes at 9:45

	Lane 1	Lane 2	Lane 3	Lane 4	Average
02ETD	2.36	1.89	0	0	2.12
03ETD	1.75	2.59	0	0	2.04
05ETD	1.19	1.17	1.25	0	1.19
08ETD	1.1	1.11	1.09	0	1.08
10ETD	1.29	1.18	1.17	0	1.22
11ETD	1.5	1.39	1.4	0	1.44
12ETD	1.9	1.93	2.11	0	1.95
13ETD	1.83	1.96	2.3	0	1.97
16ETD	1.05	1.13	1.15	0	1.13
17ETD1	1.04	1.02	1.06	1.06	1.06
18ETD	1.12	1.11	0	0	1.12
19ETD	1.4	1.35	2.85	2.51	1.8
20ETD	1.45	1.57	2.33	2.68	1.83
21ETD	1.55	1.78	4.62	4.94	2.36
22ETD	1.15	1.17	1.47	1.38	1.28
23ETD	1.07	1.01	1.09	1.12	1.07
25ETD	1.09	1.07	1.05	1.08	1.07
26ETD	1.01	1.11	1.07	1.1	1.06
27ETD	1.04	1.04	1.04	1.06	1.03

Table 3k: Travel Time Indexes at 10:00					
	Lane 1	Lane 2	Lane 3	Lane 4	Average
02ETD	1.67	1.42			1.55
03ETD	1.16	1.17			1.15
05ETD	1.07	1.13	1.13		1.1
08ETD	1.03	1.06	1.05		1.03
10ETD	1.05	1.05	1.06		1.06
11ETD	1.1	1.06	1.07		1.08
12ETD	1.04	1.15	1.11		1.09
13ETD	1.08	1.09	1.2		1.1
16ETD	0.99	1.02	1		1.02
17ETD1	1	0.95	1.02	0.98	1
18ETD	1.01	1.01			1.02
19ETD	1.02	1.02	1.13	1.07	1.06
20ETD	1.06	1.06	1.04	1.05	1.04
21ETD	1.05	1	1.04	1.1	1.05
22ETD	1.22	1.27	1.3	1.25	1.27
23ETD	1.02	1	0.99	1.03	1.01
25ETD	1.05	1.01	1	1.04	1.02
26ETD	1	1.04	1.01	1.05	1.02
27ETD	1.03	1.01	1.01	1.06	1.01

Table 3a to Table 3k show the evolution of the travel time index during the morning rush hour. The highlighted values are the higher ones which helps us to indentify critical parts and times. Almost all these parts match with the place or zone where bottlenecks are situated and the time when bottlenecks are active (Bottlenecks situation and periods when bottlenecks are active are explained in “Corridor capacities” section of the article).

Table 4a to Table 4d reveal the travel time index during the afternoon rush hour. In this period, unlike the morning rush hour, the congestion is less extended through the highway. We can identify only two bottlenecks activation in the near part of the city.

Afternoon rush hour travel time indexes (17:30-19:00):

Table 4a: Travel Time Indexes at 17:30

	Lane 1	Lane 2	Lane 3	Lane 4	Average
02ETD	1.64	1.76			1.69
03ETD	1.21	1.2			1.19
05ETD	1.06	1.09	1.13		1.08
08ETD	1.06	1.11	1.07		1.06
10ETD	1.08	1.06	1.03		1.07
11ETD	1.11	1.07	1.04		1.08
12ETD	1.07	1.11	1.15		1.09
13ETD	1.04	1.03	1.05		1.02
16ETD	1.03	1.04	1.06		1.06
17ETD1	1.01	1.01	1.02	0.99	1.02
18ETD	1.02	1.03			1.04
19ETD	1.03	0.96	1.09	1.05	1.03
20ETD	1.04	1.03	1.01	1.02	1.02
21ETD	1.05	1.02	1.03	1.02	1.03
22ETD	1.01	1.06	1.04	1.02	1.04
23ETD	1.02	1.07	1.03	1.07	1.04
25ETD	1.03	1.04	1.02	1.05	1.03
26ETD	0.99	1.06	1.05	1.02	1.02
27ETD	1.01	1.04	1.03	1.05	1.02

Table 4b: Travel Time Indexes at 18:00

	Lane 1	Lane 2	Lane 3	Lane 4	Average
02ETD	3.33	2.39			2.83
03ETD	2.92	2.64			2.75
05ETD	1.34	1.34	1.38		1.34
08ETD	1.18	1.18	1.14		1.15
10ETD	1.13	1.08	1.04		1.09
11ETD	1.11	1.11	1.05		1.1
12ETD	1.07	1.12	1.1		1.09
13ETD	1.05	1.03	1.07		1.03
16ETD	0.96	1.06	1.1		1.06
17ETD1	1	1.06	1.04	1.04	1.04
18ETD	1.01	1.05			1.04
19ETD	1.01	1.04	1.15	1.08	1.07
20ETD	0.99	1.03	1.05	1.05	1.02
21ETD	1.04	1.07	1.03	1	1.04
22ETD	1.03	1.05	1.04	1.05	1.05
23ETD	1.03	1.11	1.05	1.12	1.07
25ETD	1.07	1.06	1.04	1.06	1.05
26ETD	1.04	1.08	1.05	1.06	1.05
27ETD	1.1	1.09	1.04	1.04	1.06

Table 4c: Travel Time Indexes at 18:30

	Lane 1	Lane 2	Lane 3	Lane 4	Average
02ETD	2.46	1.7			2.05
03ETD	2.92	2.82			2.84
05ETD	3.27	2.64	2.19		2.65
08ETD	1.41	1.61	1.72		1.53
10ETD	1.19	1.14	1.09		1.15
11ETD	1.19	1.18	1.13		1.18
12ETD	1.12	1.16	1.14		1.13
13ETD	1.06	1.05	1.1		1.05
16ETD	1.03	1.1	1.14		1.11
17ETD1	0.99	1.03	1.08	1.1	1.06
18ETD	1.01	1.05			1.04
19ETD	1.05	1.05	1.18	1.12	1.09
20ETD	1.04	1.04	1.06	1.07	1.04
21ETD	1.06	1.05	1.05	1.05	1.05
22ETD	1.04	1.05	1.07	1.05	1.06
23ETD	1.05	1.03	1.09	1.06	1.05
25ETD	1.05	1.05	1.05	1.07	1.05
26ETD	1.04	1.08	1.03	1.03	1.04
27ETD	1.07	1.08	1.05	1.04	1.05

Table 4d: Travel Time Indexes at 19:00

	Lane 1	Lane 2	Lane 3	Lane 4	Average
02ETD	2.39	1.9			2.15
03ETD	2.86	2.72			2.76
05ETD	1.51	1.65	2.17		1.7
08ETD	1.09	1.25	1.16		1.14
10ETD	1.11	1.13	1.07		1.11
11ETD	1.1	1.11	1.16		1.13
12ETD	1.01	1.09	1.08		1.05
13ETD	0.99	1.03	1.06		1.01
16ETD	0.72	1.02	1.04		0.91
17ETD1	1.04	0.99	1.04	1.04	1.04
18ETD	1.02	1.06			1.05
19ETD	1.03	1.03	1.04	1.01	1.03
20ETD	1.05	1.06	1.02	1.05	1.03
21ETD	1.07	1.02	1.04	1.04	1.04
22ETD	0.99	1.02	1.05	1.06	1.04
23ETD	1.03	1.02	1.07	1.1	1.05
25ETD	1.04	1.02	1.01	1.08	1.03
26ETD	1.06	1.05	1.03	1.02	1.04
27ETD	1.06	1.06	1.04	1	1.03

Queue Evolving Diagram

We build this tool in order to show in a visible way the evolution of the congestion in the different lanes of the highway during rush hours.

We noticed that congestion appears disaggregated between lanes, i.e. the behavior between different lanes can change drastically in the same locations. We think it is important to not aggregate all the lanes and analyze it disaggregated.

This Diagram is made through several rectangular plots, each one set every certain period of time (e.g. 15 minutes). Each plot has a rectangular shape formed by a grid of cells, where each cell corresponds to one loop detector and one lane in the highway. Moreover, each cell has a different color based on the speed in that loop detector and lane. If a cell is completely white, it means that this lane does not exist in that location. The colors vary between black (10km/h) and light yellow (130km/h).

Thus, the X-axes represent the number of lanes in the different locations of the highway. While the Y-axes correspond to the different loop detectors where data comes from. However, the numbers in the Y-axes are the number of the Ramps in the highway. This way is easier to see easily the Ramps that are causing congestion.

The speed data from loop detectors 04ETD and 07ETD are calculated through averages of the neighbor loop detectors, because these two LDs are simple (they do not measure speeds). Moreover, the data of the following loop detectors are not used in Queue Evolving Diagrams:

- 17ETD2 is simple LD and it is in the same location of 17ETD1.
- 24ETD it does not measure the data of the third lane properly and it does not give us relevant/new information (the neighbor LDs are closer enough).
- 28ETD is also simple LD and it is the last one upstream.

Figure 21 presents one Queue Evolving Diagram formed by 12 plots set every 15 minutes during the morning rush hour. On the other hand, Figure 22 shows QED of afternoon rush hour.

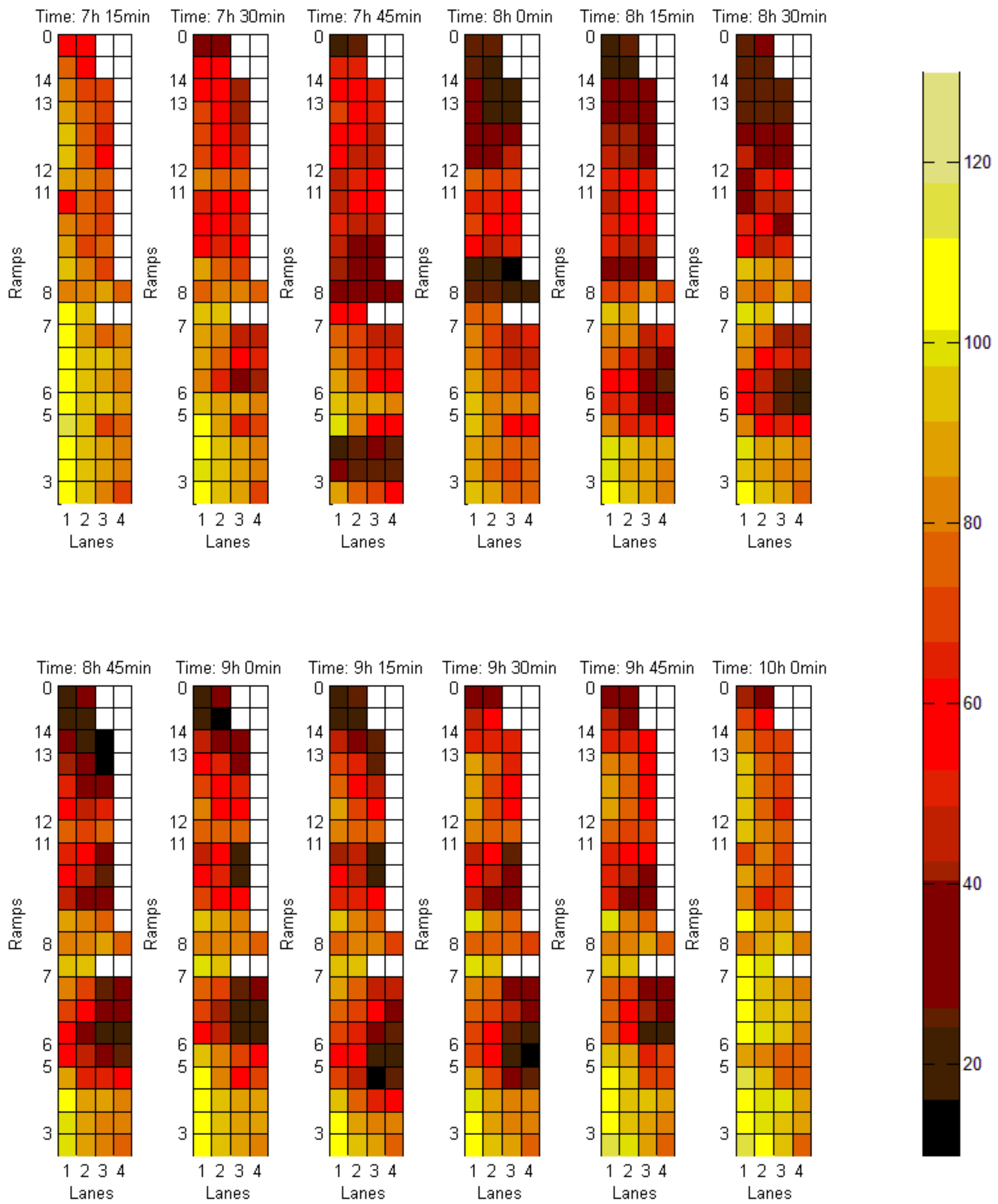


Figure 21: Queue Evolution Diagram based on speeds(KM/H) of the morning rush hour

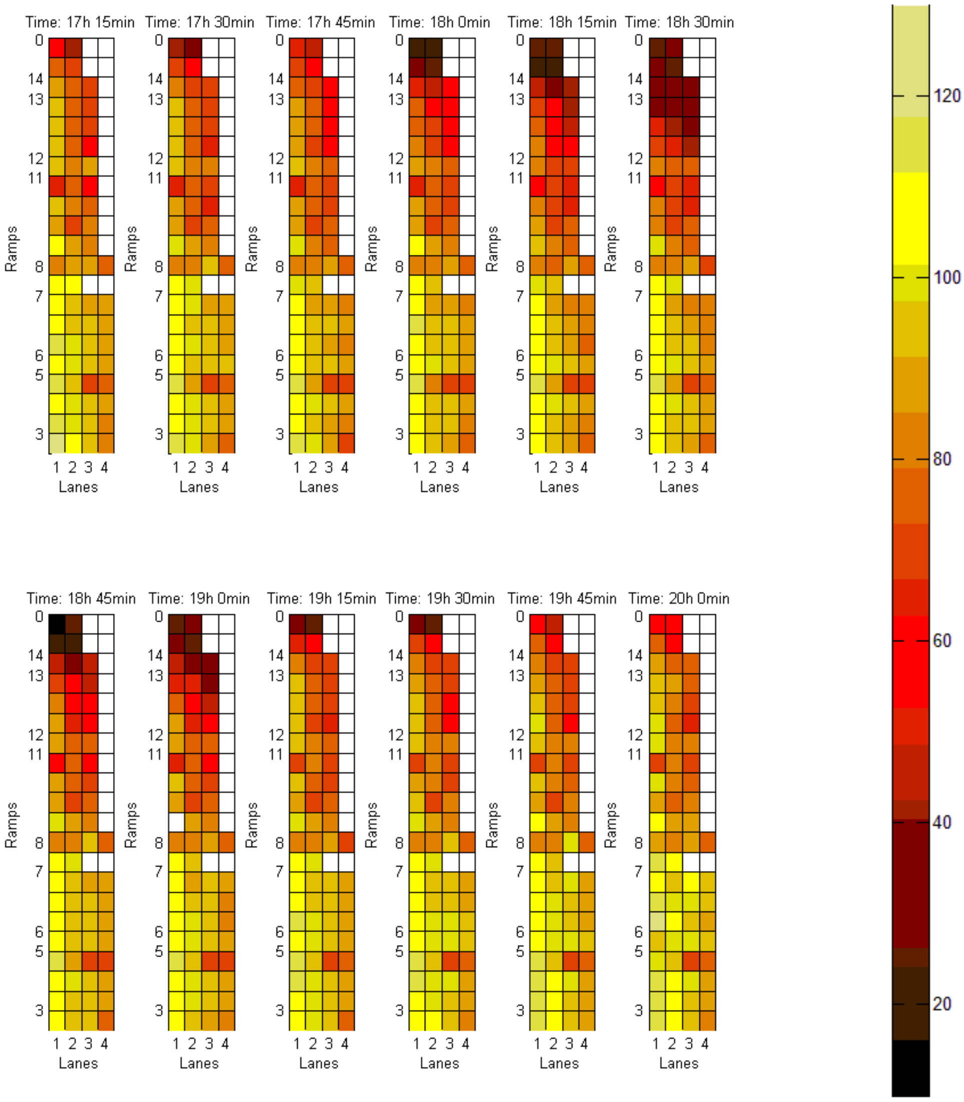
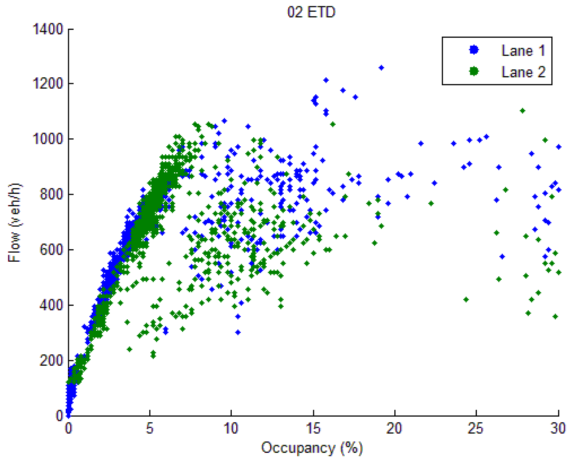
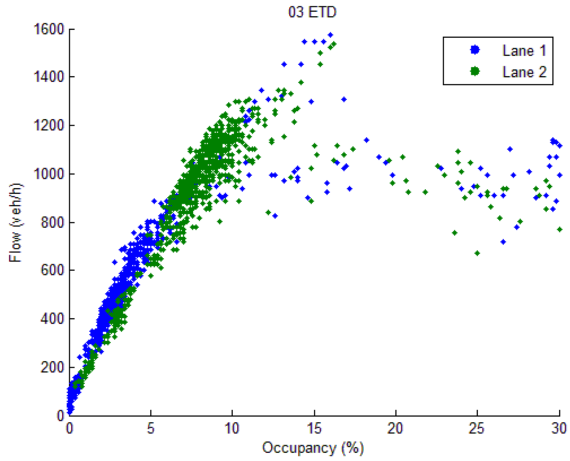


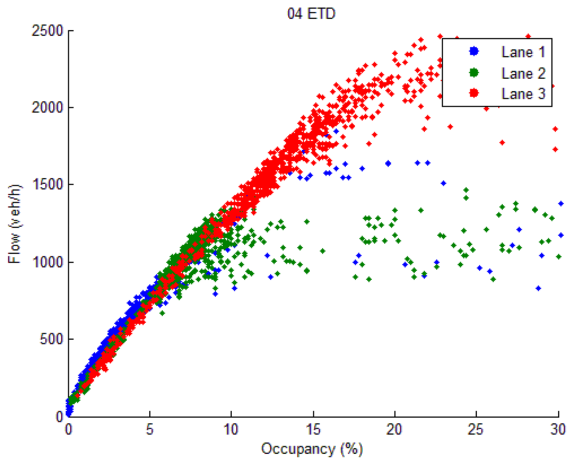
Figure 22: Queue Evolution Diagram based on speeds(KM/H) of the afternoon rush hour

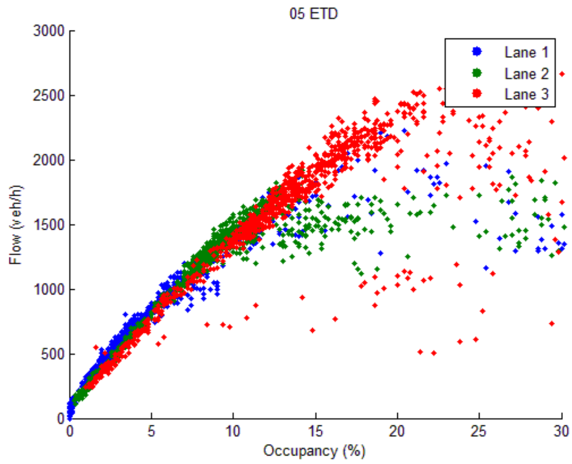
D. Figures Recompilation

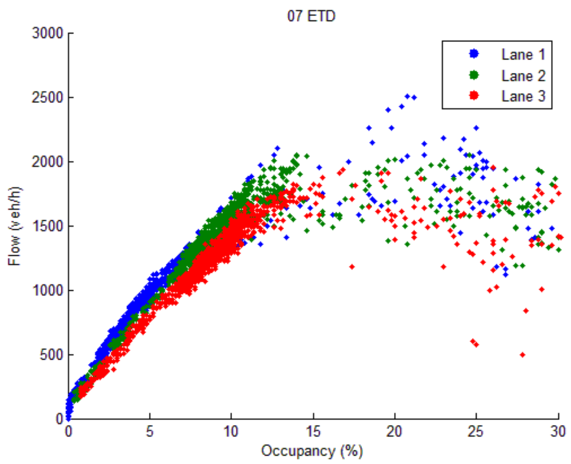
Fundamental diagrams

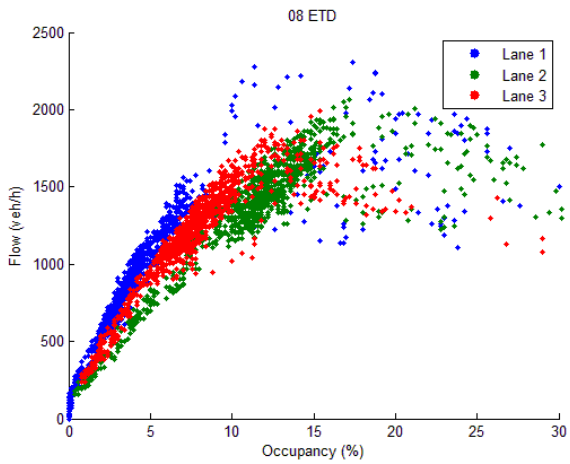


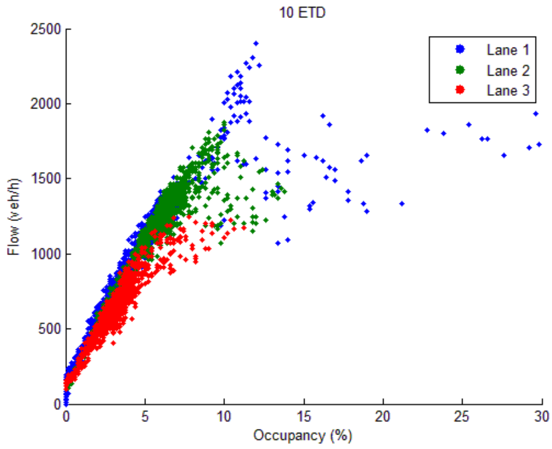


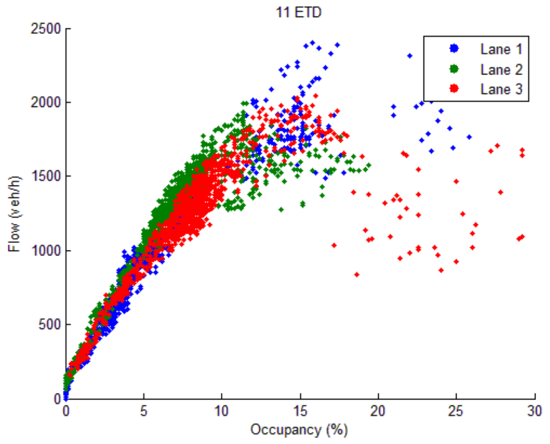


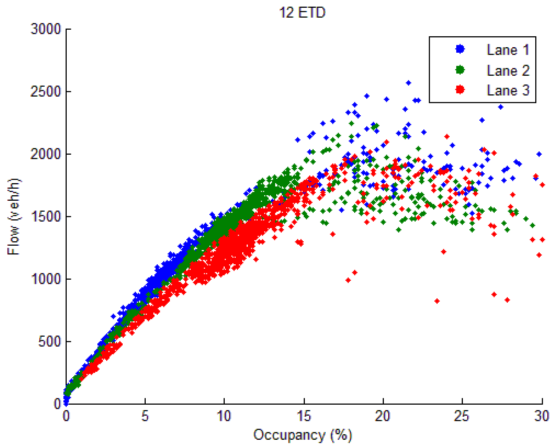


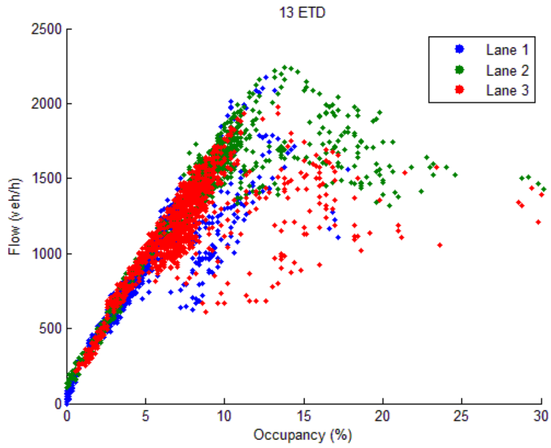


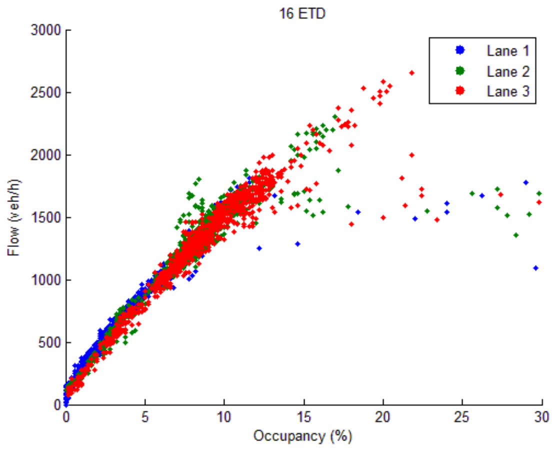


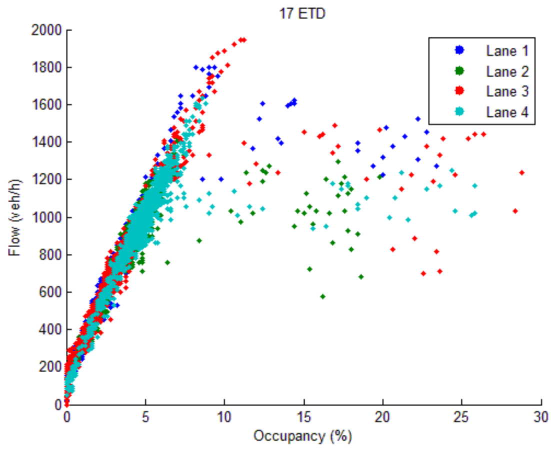

10 ETD
Flow (veh/h)
Occupancy (%)
Lane 1
Lane 2
Lane 3

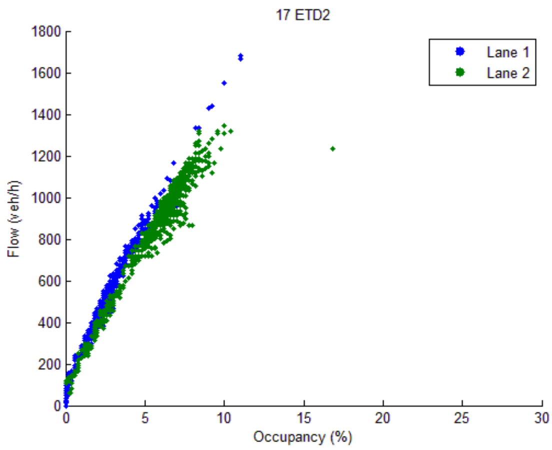

11 ETD
Flow (veh/h)
Occupancy (%)
Lane 1
Lane 2
Lane 3

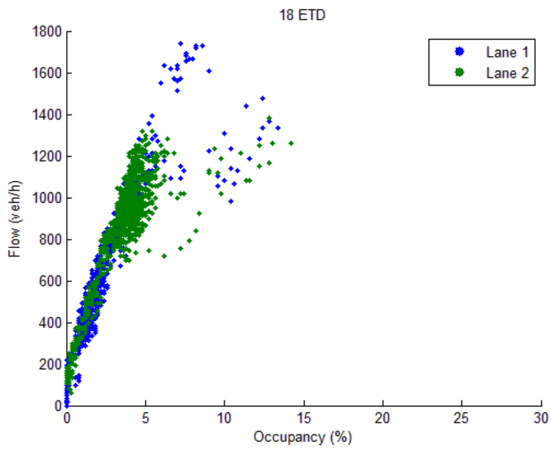

12 ETD
Flow (veh/h)
Occupancy (%)
Lane 1
Lane 2
Lane 3

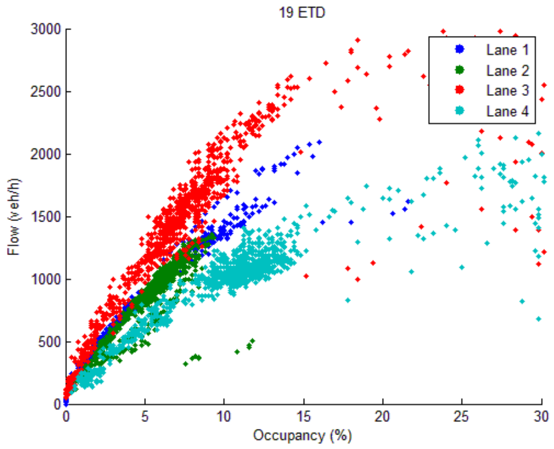

13 ETD
Flow (veh/h)
Occupancy (%)
Lane 1
Lane 2
Lane 3

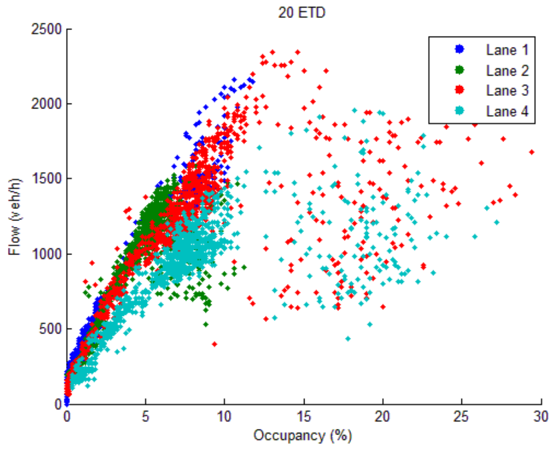

16 ETD
Flow (veh/h)
Occupancy (%)
Lane 1
Lane 2
Lane 3

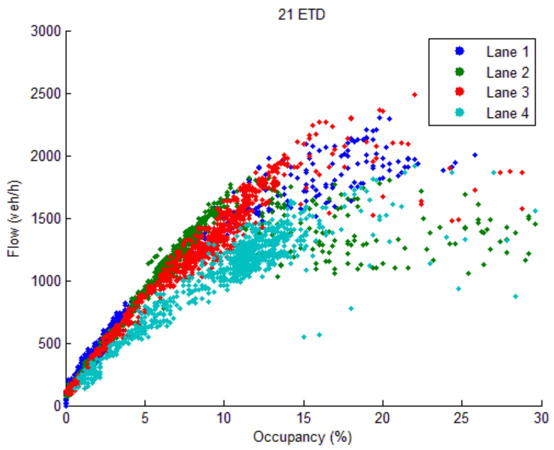

17 ETD
Flow (veh/h)
Occupancy (%)
Lane 1
Lane 2
Lane 3
Lane 4

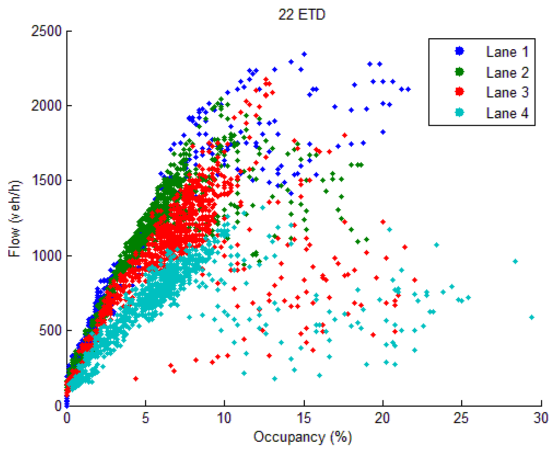

17 ETD2
Flow (veh/h)
Occupancy (%)
Lane 1
Lane 2

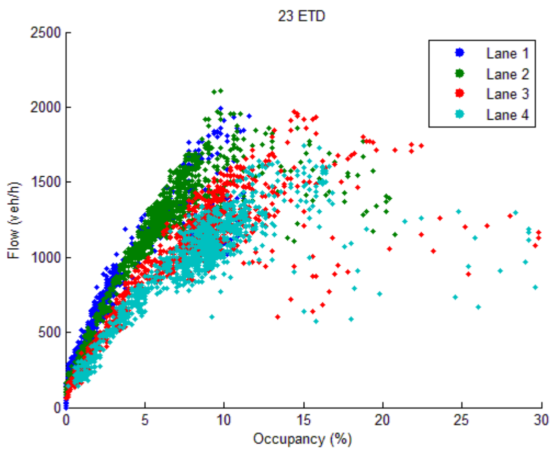

18 ETD
Flow (veh/h)
Occupancy (%)
Lane 1
Lane 2

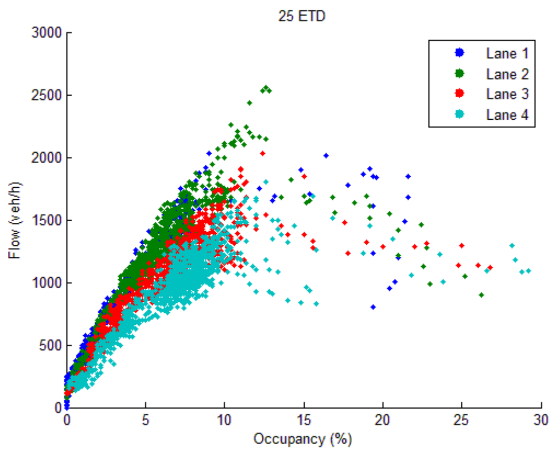

19 ETD
Lane 1
Lane 2
Lane 3
Lane 4
Flow (veh/h)
Occupancy (%)

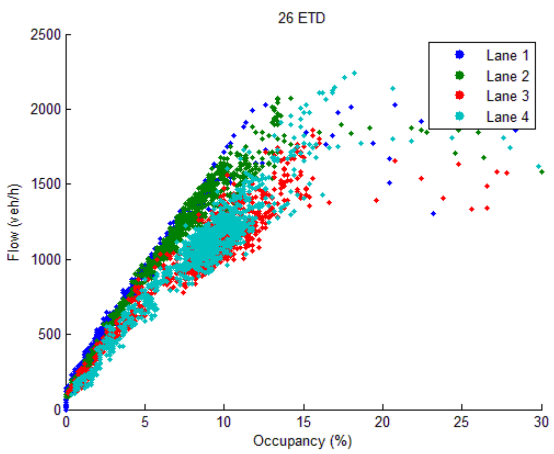

20 ETD
Lane 1
Lane 2
Lane 3
Lane 4
Flow (veh/h)
Occupancy (%)

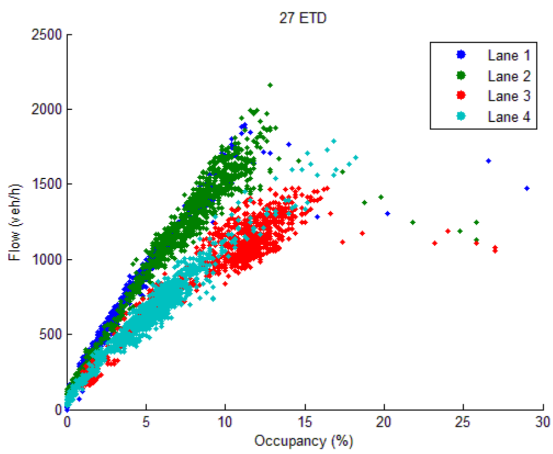

21 ETD
Lane 1
Lane 2
Lane 3
Lane 4
Flow (veh/h)
Occupancy (%)

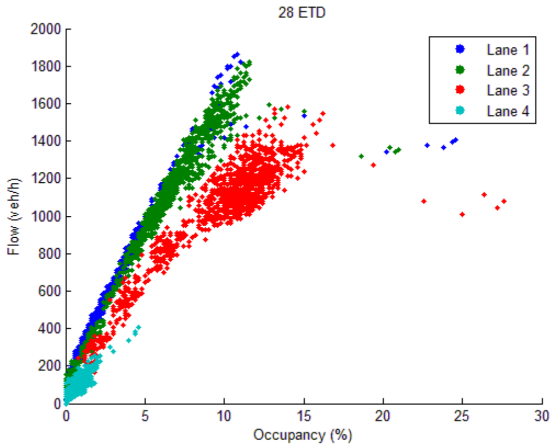

22 ETD
Lane 1
Lane 2
Lane 3
Lane 4
Flow (veh/h)
Occupancy (%)


23 ETD
Lane 1
Lane 2
Lane 3
Lane 4
Flow (veh/h)
Occupancy (%)

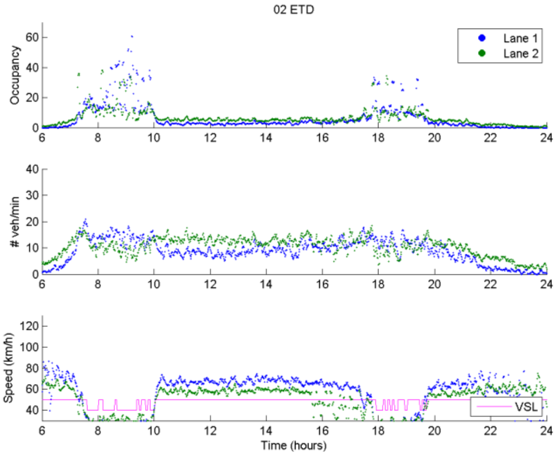

25 ETD
Lane 1
Lane 2
Lane 3
Lane 4
Flow (veh/h)
Occupancy (%)

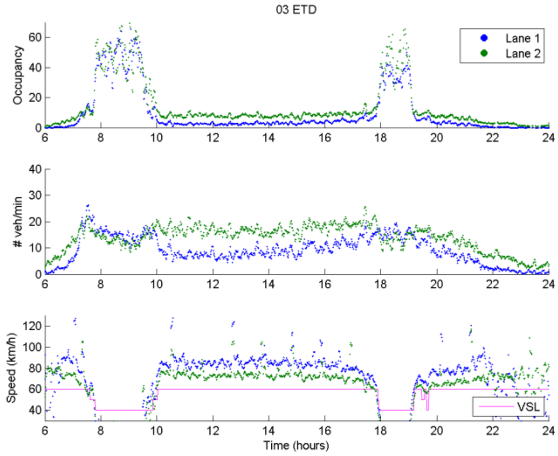

26 ETD
Lane 1
Lane 2
Lane 3
Lane 4
Flow (veh/h)
Occupancy (%)

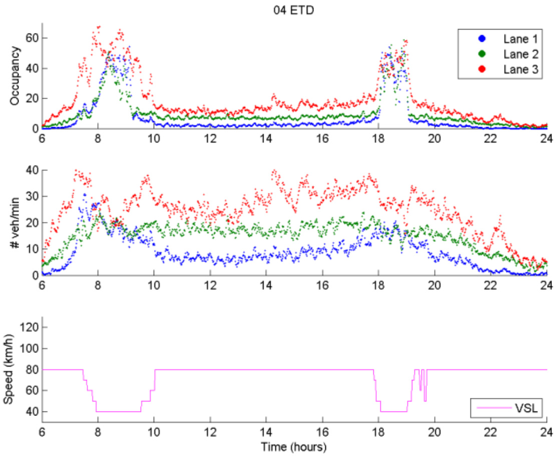

27 ETD
Lane 1
Lane 2
Lane 3
Lane 4
Flow (veh/h)
Occupancy (%)

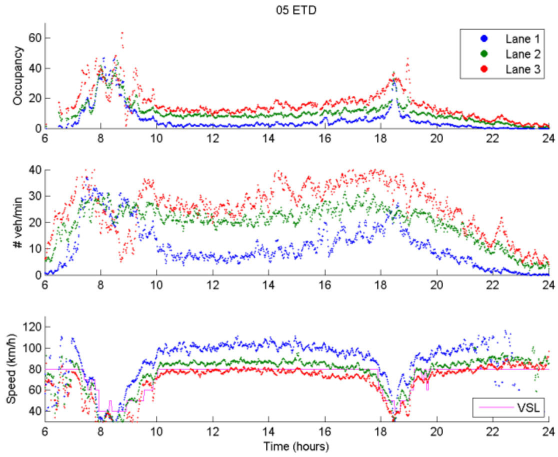

28 ETD
Lane 1
Lane 2
Lane 3
Lane 4
Flow (veh/h)
Occupancy (%)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0
5
10
15
20
25
30

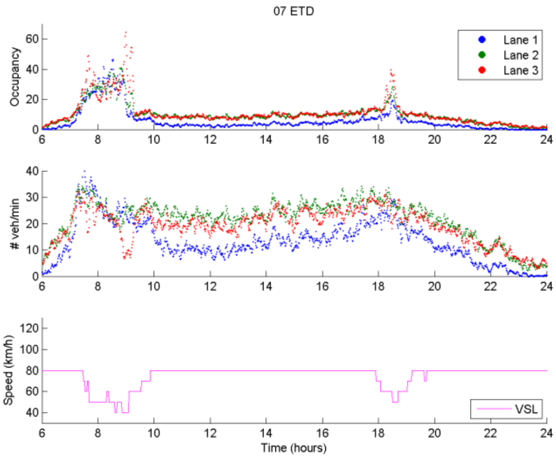
Subplots of occupancies, flows and speeds during the entire day

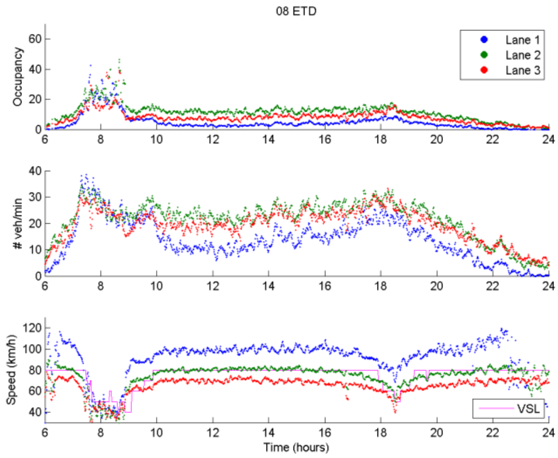


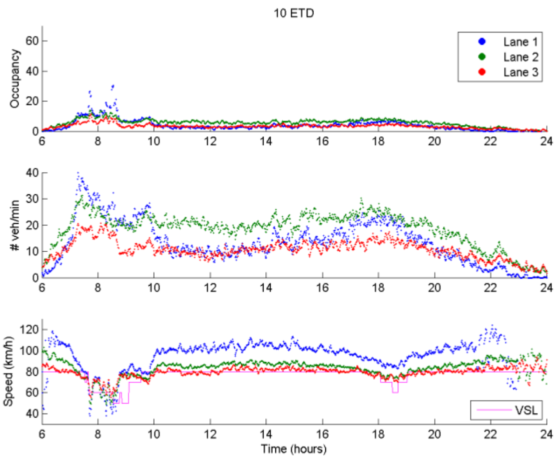


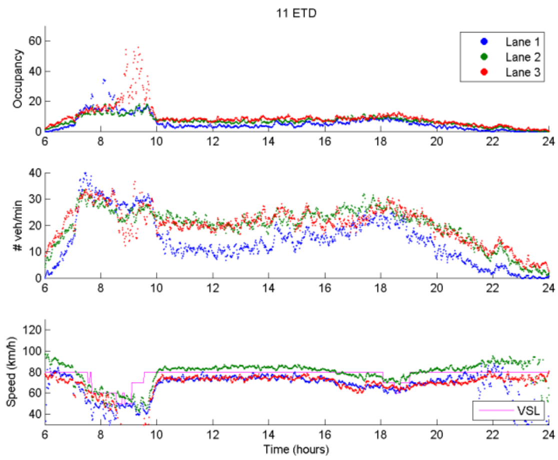


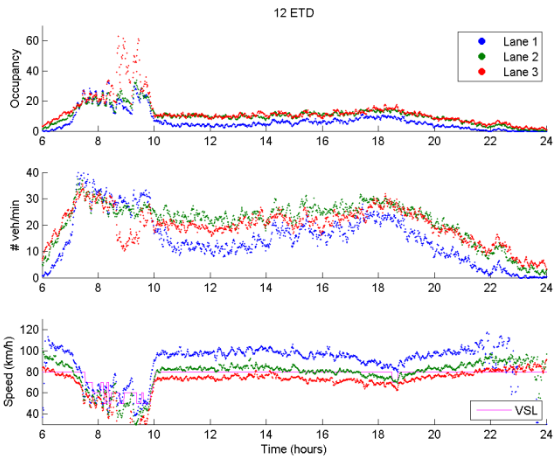


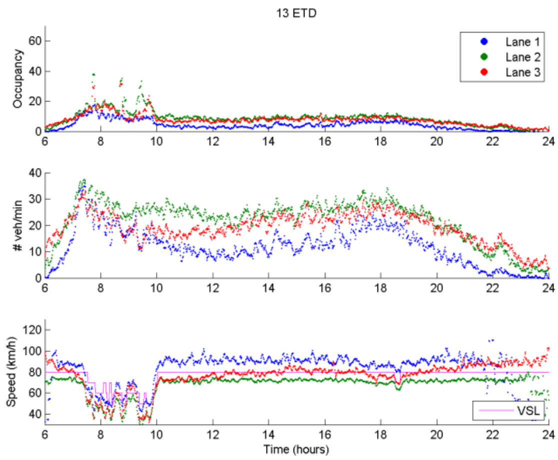


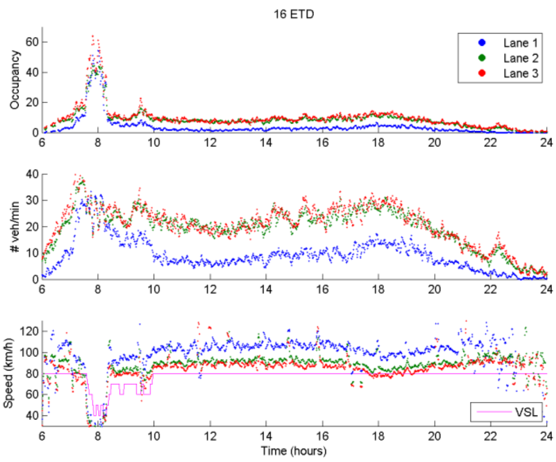


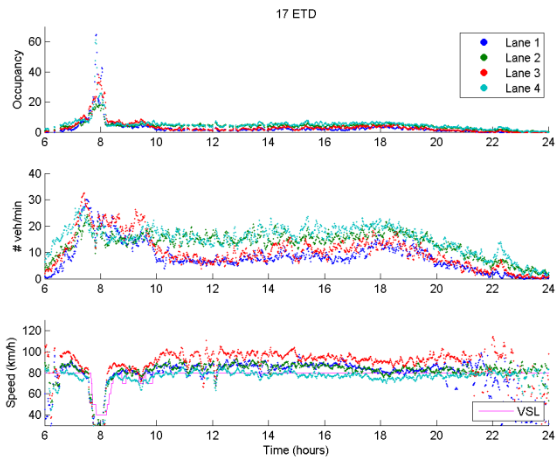

10 ETD
Occupancy
veh/min
Speed (km/h)
Time (hours)
Lane 1
Lane 2
Lane 3
VSL

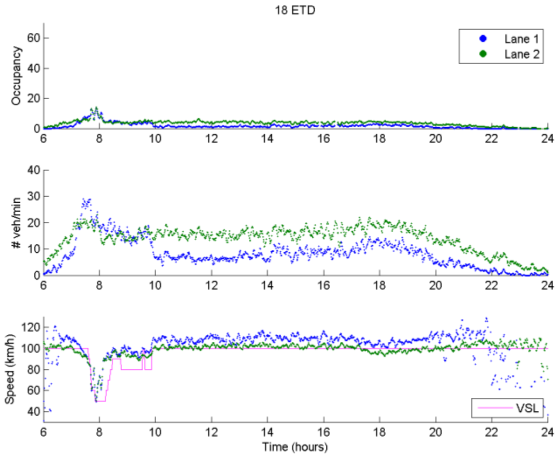

11 ETD
Occupancy
veh/min
Speed (km/h)
Time (hours)
Lane 1
Lane 2
Lane 3
VSL

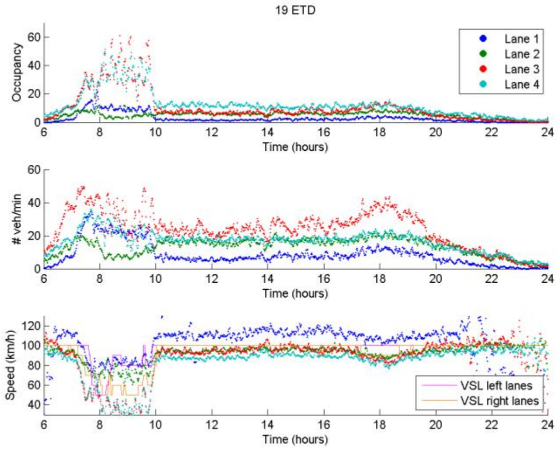

12 ETD
Occupancy
veh/min
Speed (km/h)
Time (hours)
Lane 1
Lane 2
Lane 3
VSL

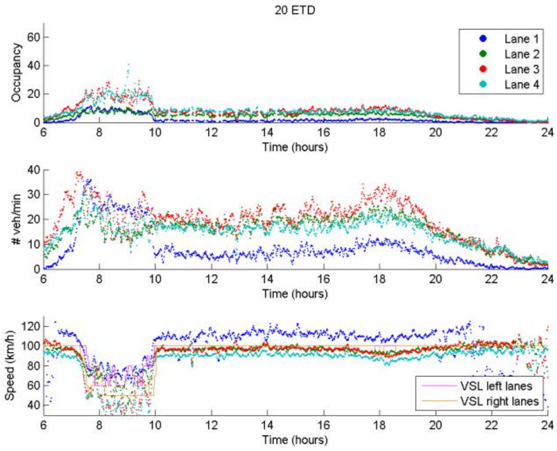

13 ETD
Occupancy
veh/min
Speed (km/h)
Time (hours)
Lane 1
Lane 2
Lane 3
VSL


16 ETD
Occupancy
veh/min
Speed (km/h)
Time (hours)
Lane 1
Lane 2
Lane 3
VSL


17 ETD
Occupancy
veh/min
Speed (km/h)
Time (hours)
Lane 1
Lane 2
Lane 3
Lane 4
VSL


18 ETD
Occupancy
veh/min
Speed (km/h)
Time (hours)
Lane 1
Lane 2
VSL


19 ETD
Occupancy
veh/min
Speed (km/h)
Time (hours)
Lane 1
Lane 2
Lane 3
Lane 4
VSL left lanes
VSL right lanes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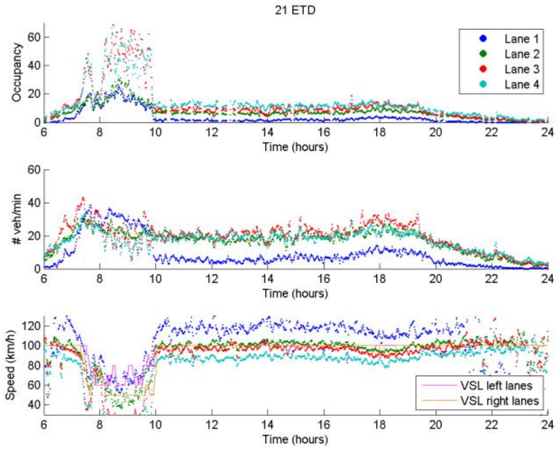
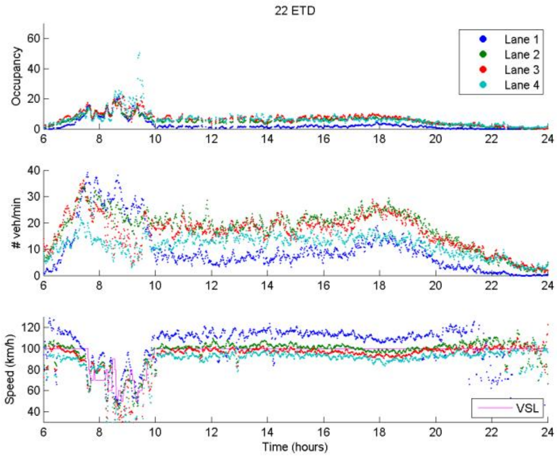
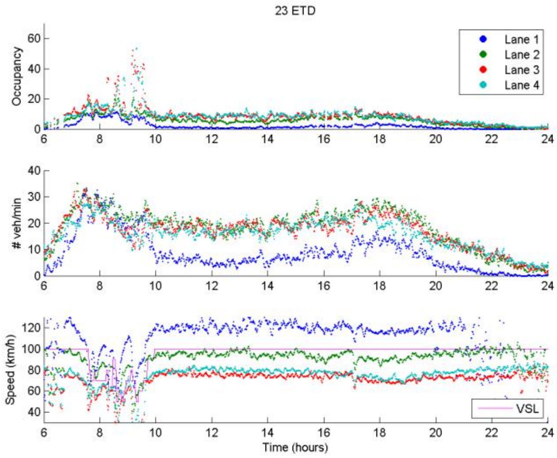
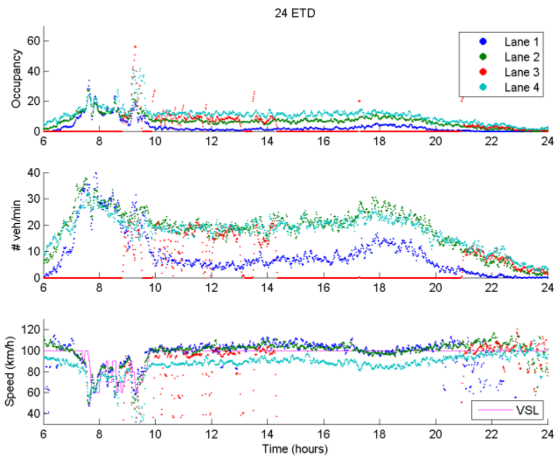
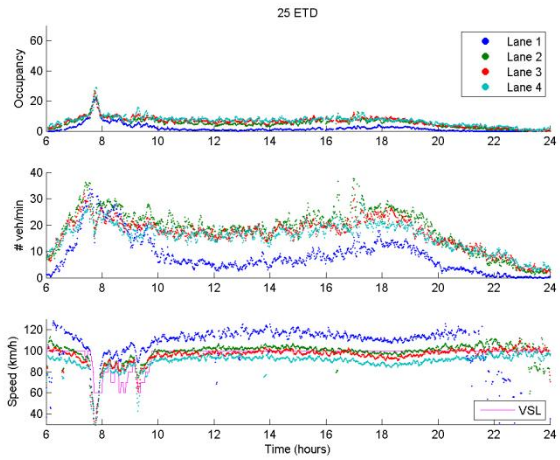
Occupancy
veh/min
Speed (km/h)
Time (hours)
Lane 1
Lane 2
Lane 3
Lane 4
VSL left lanes
VSL right lanes

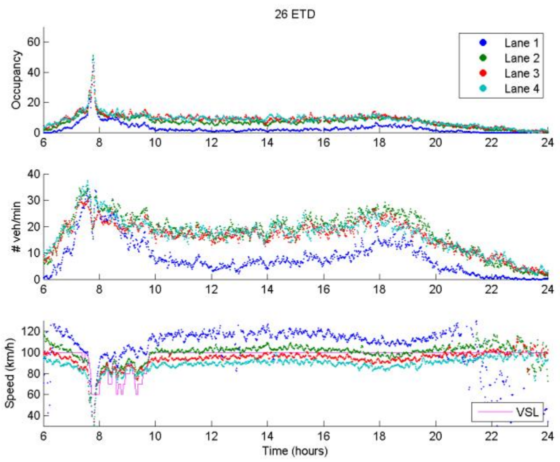

21 ETD
Occupancy
veh/min
Speed (km/h)
Time (hours)
Lane 1
Lane 2
Lane 3
Lane 4
VSL left lanes
VSL right lanes

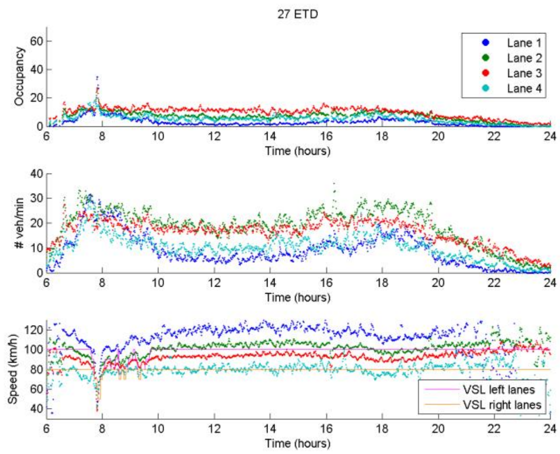

22 ETD
Occupancy
veh/min
Speed (km/h)
Time (hours)
Lane 1
Lane 2
Lane 3
Lane 4
VSL

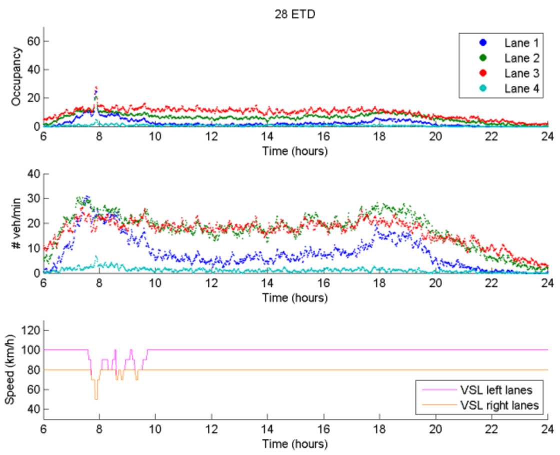

23 ETD
Occupancy
veh/min
Speed (km/h)
Time (hours)
Lane 1
Lane 2
Lane 3
Lane 4
VSL


24 ETD
Occupancy
veh/min
Speed (km/h)
Lane 1
Lane 2
Lane 3
Lane 4
VSL
Time (hours)

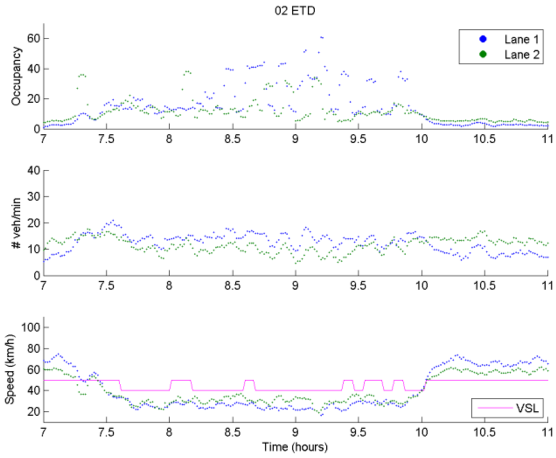

25 ETD
Occupancy
veh/min
Speed (km/h)
Lane 1
Lane 2
Lane 3
Lane 4
VSL
Time (hours)

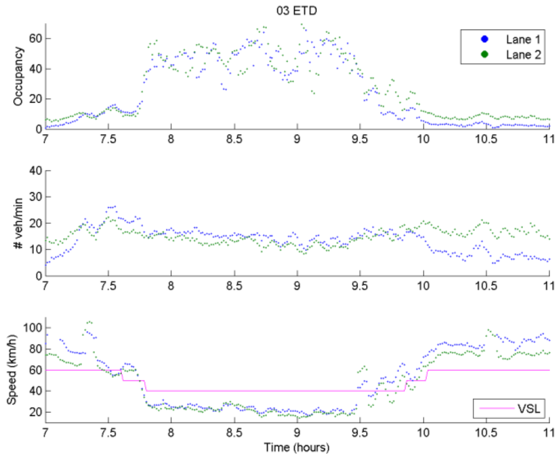

26 ETD
Occupancy
veh/min
Speed (km/h)
Lane 1
Lane 2
Lane 3
Lane 4
VSL
Time (hours)

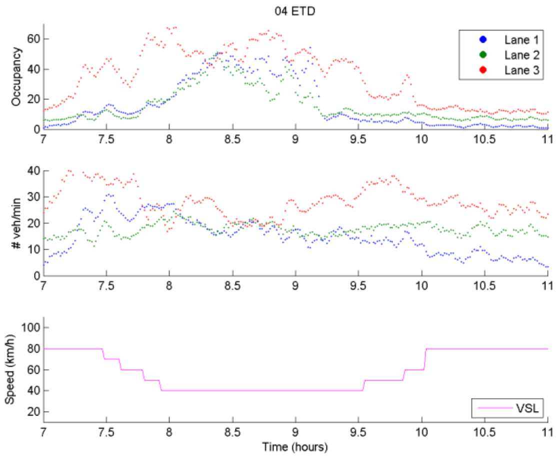

27 ETD
Occupancy
veh/min
Speed (km/h)
Lane 1
Lane 2
Lane 3
Lane 4
VSL left lanes
VSL right lanes
Time (hours)

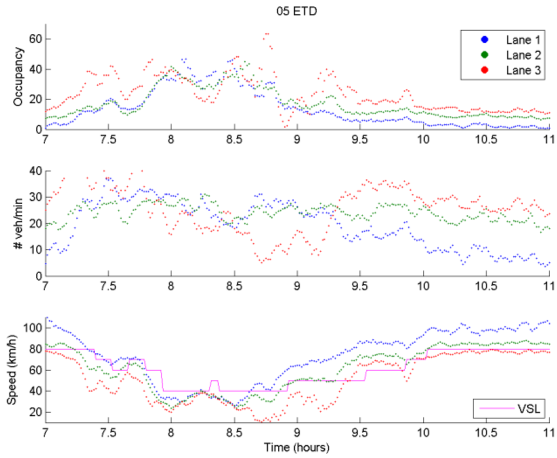

28 ETD
Occupancy
veh/min
Speed (km/h)
Lane 1
Lane 2
Lane 3
Lane 4
VSL left lanes
VSL right lanes
Time (hours)

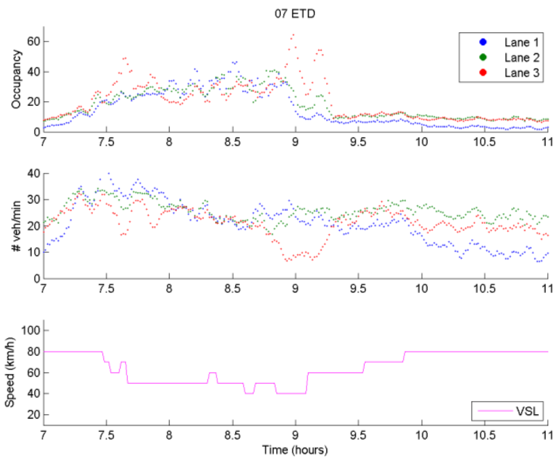
Subplots during morning rush hour

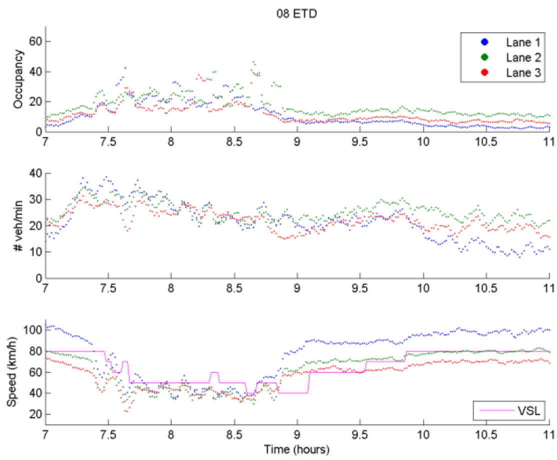


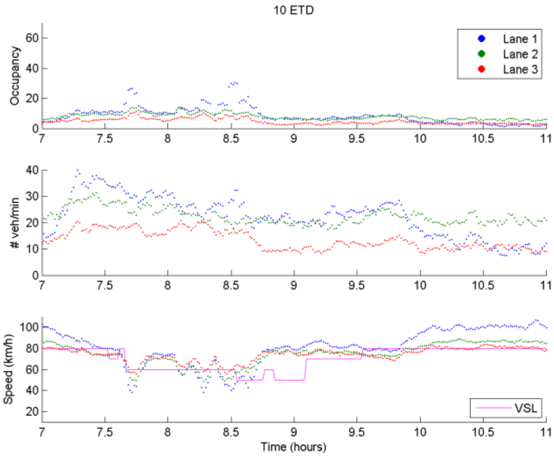


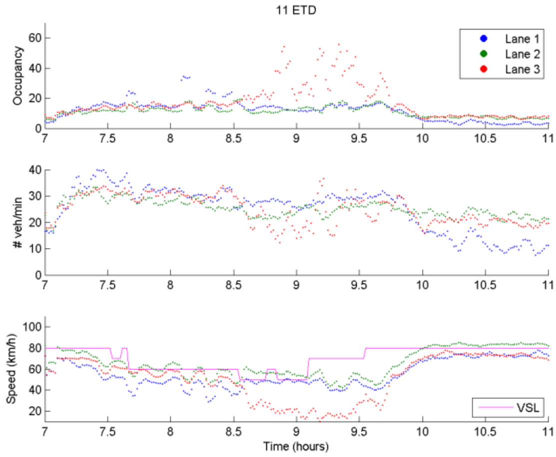


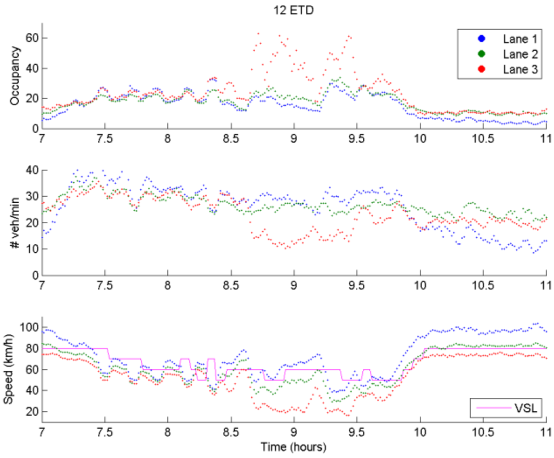


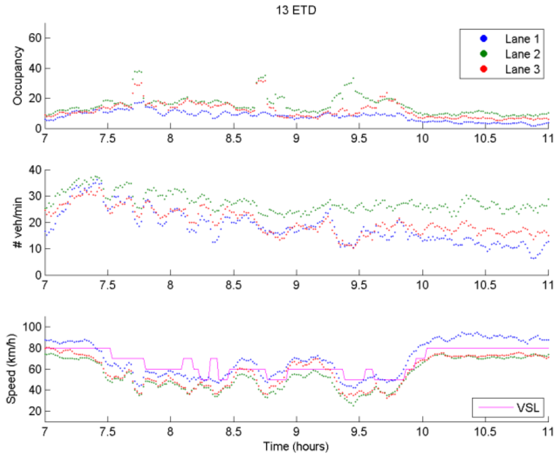


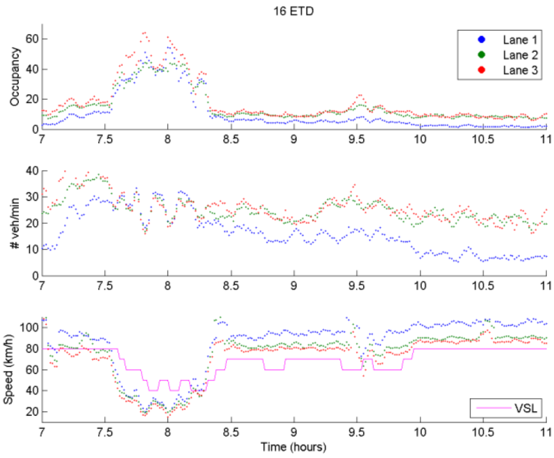


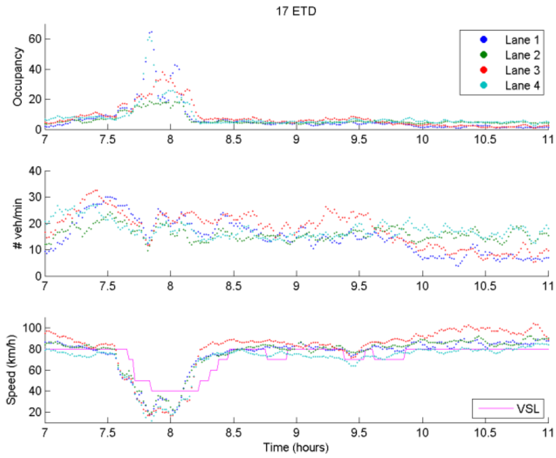

10 ETD
Occupancy
veh/min
Speed (km/h)
Time (hours)
Lane 1
Lane 2
Lane 3
VSL

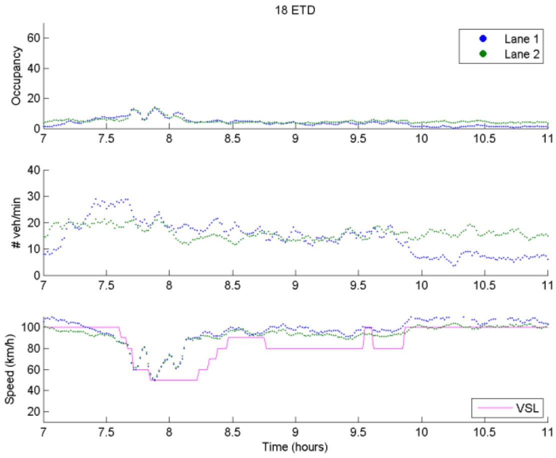

11 ETD
Occupancy
veh/min
Speed (km/h)
Time (hours)
Lane 1
Lane 2
Lane 3
VSL

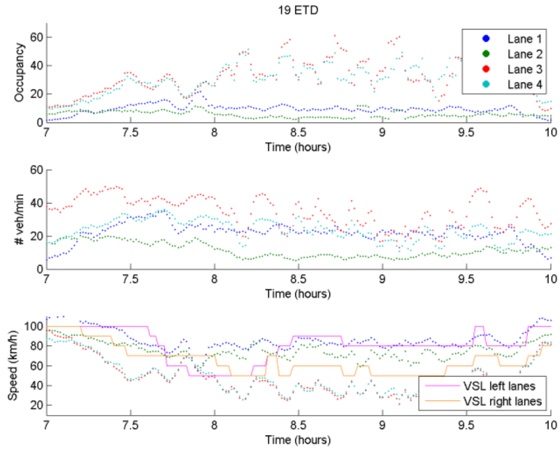

12 ETD
Occupancy
veh/min
Speed (km/h)
Time (hours)
Lane 1
Lane 2
Lane 3
VSL

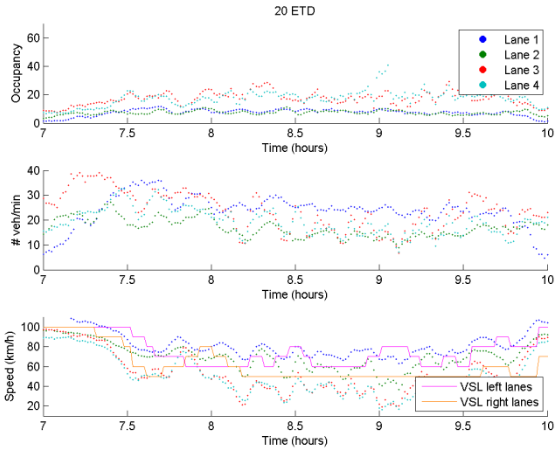

13 ETD
Occupancy
veh/min
Speed (km/h)
Time (hours)
Lane 1
Lane 2
Lane 3
VSL

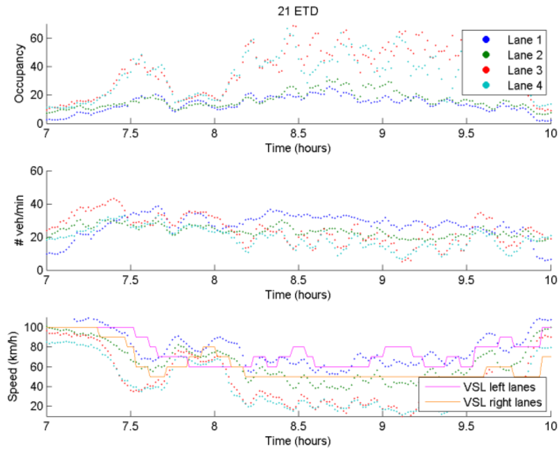

16 ETD
Occupancy
veh/min
Speed (km/h)
Time (hours)
Lane 1
Lane 2
Lane 3
VSL

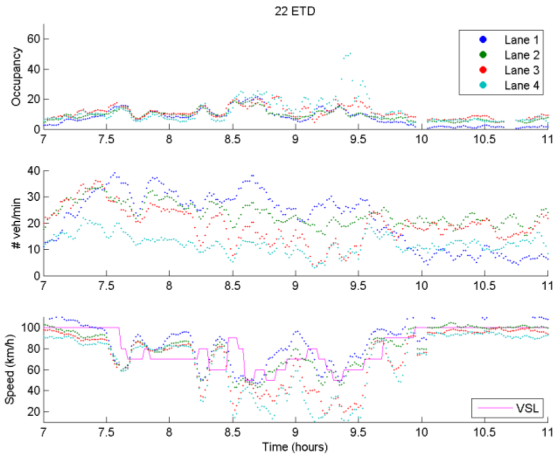

17 ETD
Occupancy
veh/min
Speed (km/h)
Time (hours)
Lane 1
Lane 2
Lane 3
Lane 4
VSL

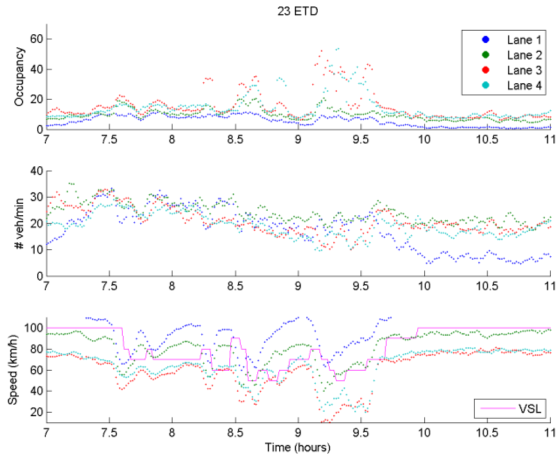

18 ETD
Occupancy
Lane 1
Lane 2
veh/min
Speed (km/h)
VSL
Time (hours)

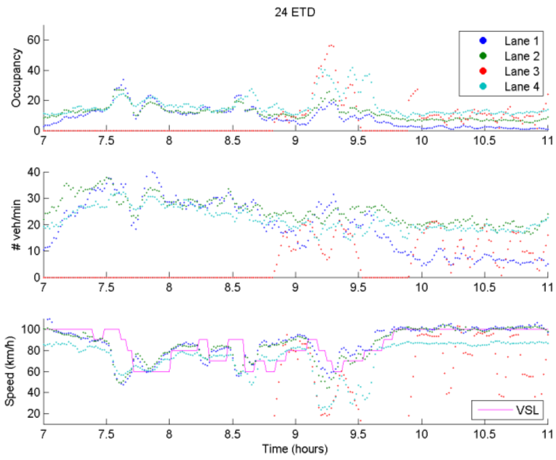

19 ETD
Occupancy
Lane 1
Lane 2
Lane 3
Lane 4
Time (hours)
veh/min
Speed (km/h)
VSL left lanes
VSL right lanes

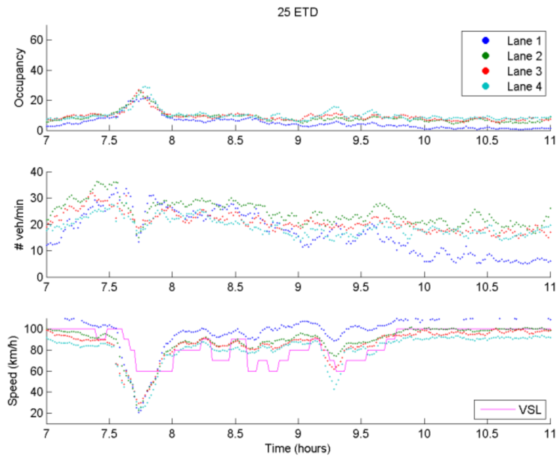

20 ETD
Occupancy
Lane 1
Lane 2
Lane 3
Lane 4
Time (hours)
veh/min
Speed (km/h)
VSL left lanes
VSL right lanes

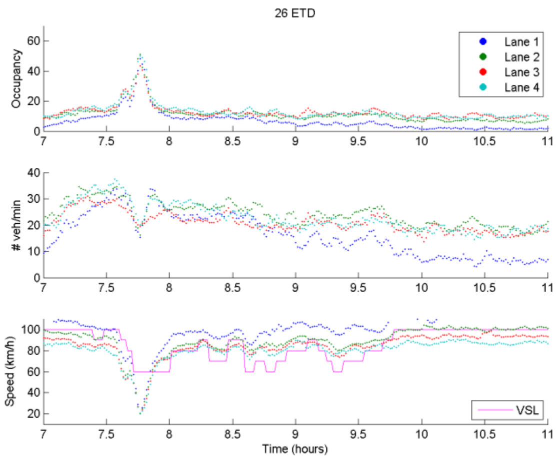

21 ETD
Occupancy
Lane 1
Lane 2
Lane 3
Lane 4
Time (hours)
veh/min
Speed (km/h)
VSL left lanes
VSL right lanes

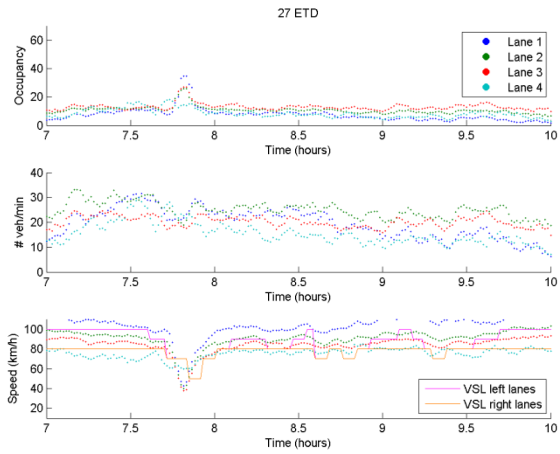

22 ETD
Occupancy
Lane 1
Lane 2
Lane 3
Lane 4
veh/min
Speed (km/h)
VSL
Time (hours)

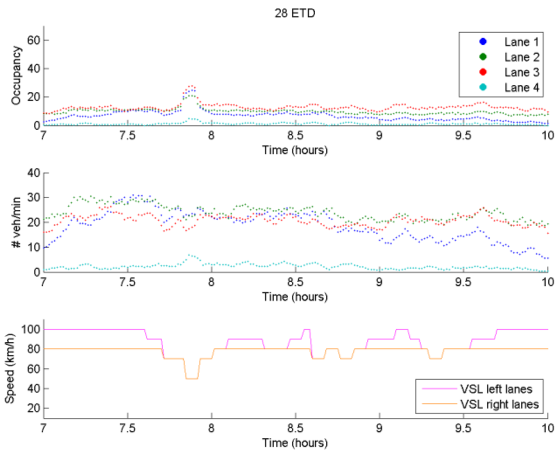

23 ETD
Occupancy
Lane 1
Lane 2
Lane 3
Lane 4
veh/min
Speed (km/h)
VSL
Time (hours)


24 ETD
Occupancy
Lane 1
Lane 2
Lane 3
Lane 4
veh/min
Speed (km/h)
VSL
Time (hours)

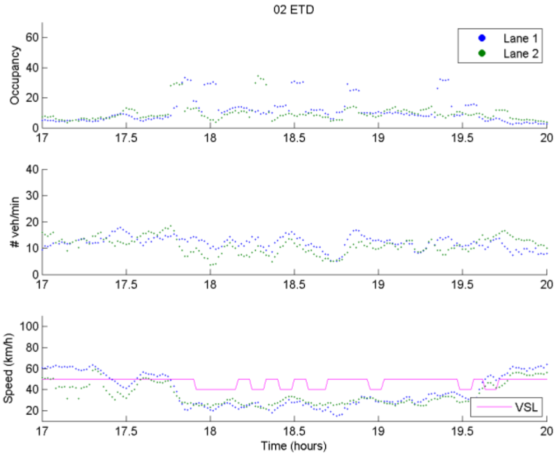

25 ETD
Occupancy
Lane 1
Lane 2
Lane 3
Lane 4
veh/min
Speed (km/h)
VSL
Time (hours)

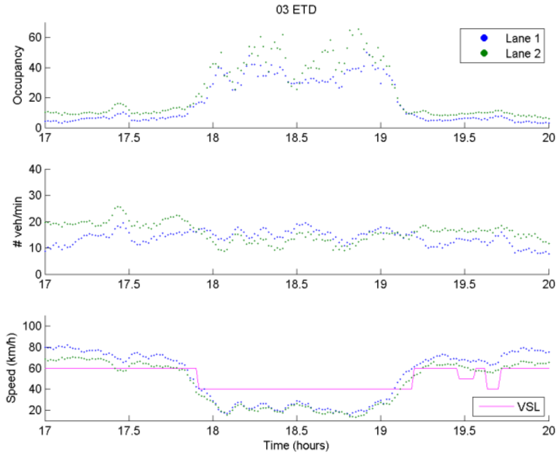

26 ETD
Occupancy
Lane 1
Lane 2
Lane 3
Lane 4
veh/min
Speed (km/h)
VSL
Time (hours)

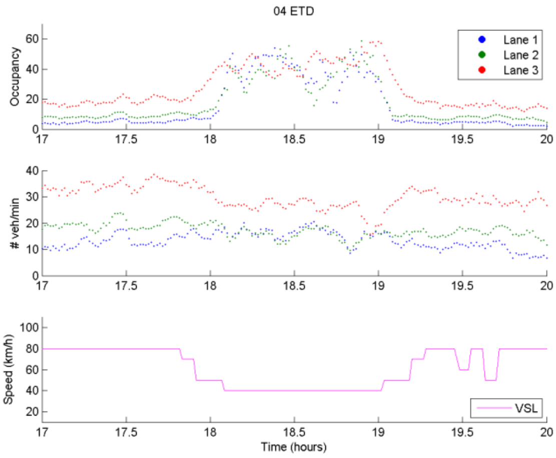

27 ETD
Occupancy
Lane 1
Lane 2
Lane 3
Lane 4
Time (hours)
veh/min
Time (hours)
Speed (km/h)
VSL left lanes
VSL right lanes
Time (hours)

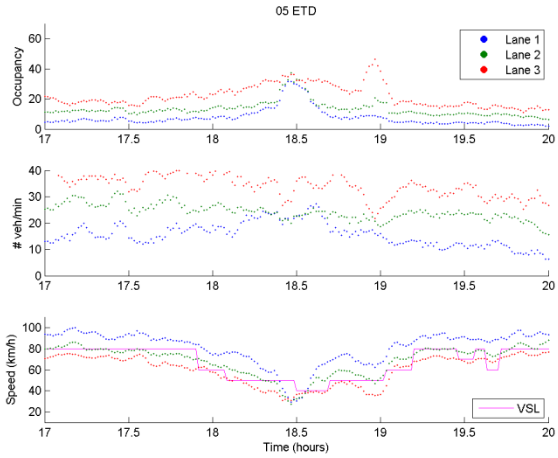

28 ETD
Occupancy
Lane 1
Lane 2
Lane 3
Lane 4
Time (hours)
veh/min
Time (hours)
Speed (km/h)
VSL left lanes
VSL right lanes
Time (hours)

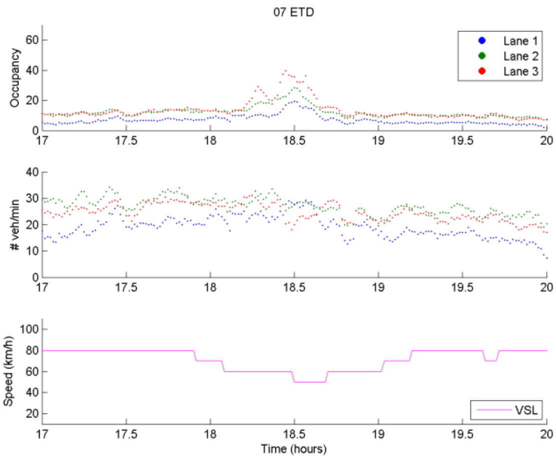
Subplots during afternoon rush hour in sections affected by the congestion

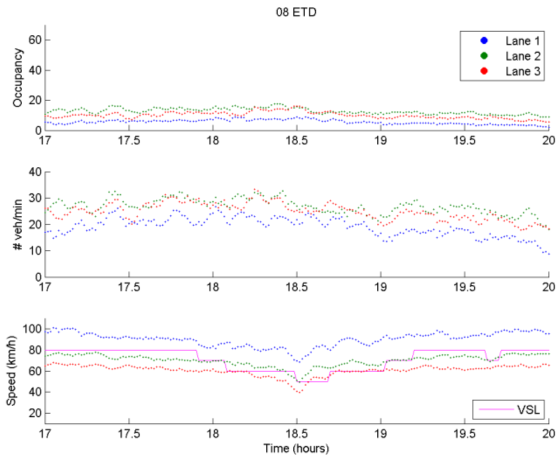


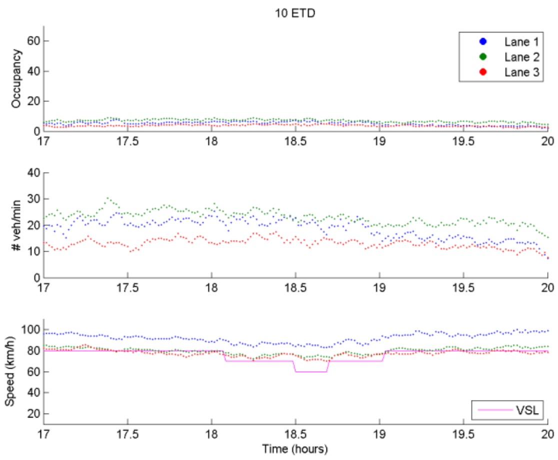


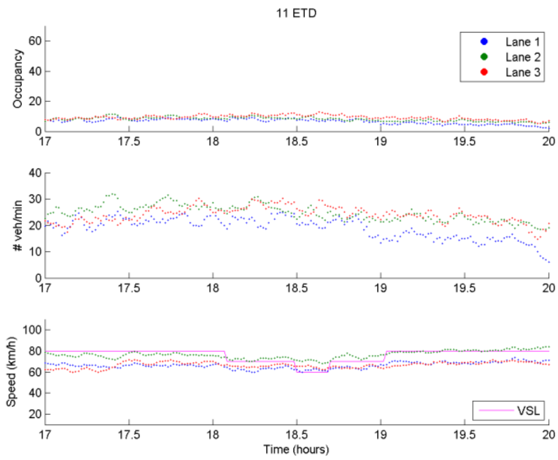


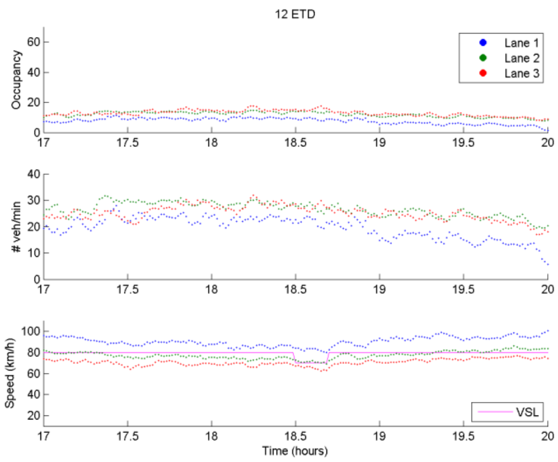







10 ETD
Occupancy
veh/min
Speed (km/h)
Time (hours)
Lane 1
Lane 2
Lane 3
VSL


11 ETD
Occupancy
veh/min
Speed (km/h)
Time (hours)
Lane 1
Lane 2
Lane 3
VSL


12 ETD
Occupancy
veh/min
Speed (km/h)
Time (hours)
Lane 1
Lane 2
Lane 3
VSL

E. Matlab workspace

We have used Matlab as a tool for making numerical computation analysis of our data sets. Additionally, we have used it to generate plots showing the data and results. In order to be able to do all this in a proper way we programmed many functions and scripts in Matlab. Moreover, we have used some punctual excel files to provide to matlab specific sets of data.

In this part of the Annex we explain shortly all the matlab files used in the Thesis. First of all we have to distinguish between three different types of matlab files: data files, functions and scripts.

Data files: These files contain the different data sets used in the scripts and functions. They do not make any numerical operation for themselves. We have data files in Matlab and Excel format.

Functions: This type of matlab file is programmed when there is some operation you use frequently and it is not already a predefined function in Matlab. They work in the same way as mathematical functions; you provide a set of inputs and the function gives you a set of outputs, with the property that each input is related to one output. The function usually does some numerical computation before giving the outputs.

Scripts: These files are a set of lines in matlab language that are saved in order to be used when you need them. These programmed lines can make the numerical computation and create the figures you want.

DATA FILES:

Name	Description
b23_data_121212.mat	Original measured data provided by 'Servei Català de Trànsit'
hwb23O.mat	Original data with structure changed
hwb23FZ.mat	Data with the new structure and zero errors fixed
hwb23O.mat	Data with the new structure, zero errors fixed and drift errors fixed
DSL.mat	Data of all the variable speed limits
DSL.xls	Data of all the variable speed limits in excel format
FFS.xlsx	Free flow speeds data in excel format
VSL2.xlsx	Relation of the speed limits in each location in uncongested periods

FUNCTIONS:

Name	Description
acum.m	Returns the cumulative sum of one vector
EffLe.me	Returns the effective length calculated with statiscal methods with the data of one loop detector
M5s.m	Returns the average time mean speed of a set of 5 minutes data of one specific loop detector, in a fixed time and one lane
MA.m	Returns the moving average vector, average within 5 minutes
plotmeocc.m	Returns a figure with the occupancies of the loop detector you choose during the entire day
plotmespeeds.m	Returns a figure with the time mean speeds of the loop detector you choose during the entire day
plotmevol.m	Returns a figure with the flow of the loop detector you choose during the entire day

SCRIPTS:

Name	Description
BNCapacity.m	Creates a figure where it plots transformed cumulative curve counts of one LD during a period of time
compare_speeds.m	Creates a figure where it is plotted the different measured speeds of each lane and VSL during a period of time
cons_hwb23.m	Creates a new data set with new structure from the original data set
contourplot.m	Generates the contourplot of occupancies in 2D
contourplot3D.m	Creates the occupancies contourplot in 3D
CreateP.m	Generates a matrix with occupancy data, which is needed to make the contourplots
CumOccN.m	Creates a figure where it plots the cumulative flow and cumulative occupancies curves of one LD data during a period of time
CumOccNLane.m	Creates a figure where it plots the cumulative flow and cumulative occupancies curves of one LD and lane data during a period of time
cumplot.m	Generates a figure where cumulative flow curves of different LD data during a period of time are plotted
DeMxSeC.m	Creates a figure where it is shown the total number of cars that passes throw each LD during a long time. It also attaches the number of lanes in each LD location.
DriftCorr.m	Fixes drift error of the LD you introduce from another LD you give as a reference
DriftCorr.11_12m	Fixes drift error data of 16ETD from data of 17ETD
EffLength.m	Generates one figure with the probabilistic density of the effectives lengths per lane of one LD
FDxlane.m	Creates in the same figure the fundamental diagrams of each lane with different colors
FixZE.m	Fixes zero error of all LD
plot_FFS.m	Generates a figure where it is compared the free flow speeds in each lane with the speed limits
PlotFlowAllLanes.m	Creates a figure where it is plotted the sum of all the lanes vehicle counts during the entire day
QED.m	Creates a figure with the Queue Evolving Diagram
Sec7fig1.m	Generates a figure where it is shown occupancies of 04ETD during the morning rush hour
Sec7fig2.m	Creates a subplot with flows and speeds data of 16ETD
Subplot_q_occ_vMA.m	Generates a figure where three plots of the three types of data (occupancy, flow and speeds) of all LDs during the same period time can be distinguished
Subplot_q_occ_vMA2.m	Creates the same as the previous script but using two sources of the VSL data
TCumOccN.m	Creates a figure in order to detect bottleneck activation through transformed cumulative curves of the data of one LD (uses the data of all the lanes)
TCumOccNLane.m	Creates a figure in order to detect bottleneck activation through transformed cumulative curves of the data of one LD (uses the data of only one lane)
TCumOccN_deact.m	Creates a figure in order to detect bottleneck deactivation through transformed cumulative curves of the data of one LD (uses the data all the lanes)
TCumOccNLane_deact.m	Creates a figure in order to detect bottleneck deactivation through transformed cumulative curves of the data of one LD (uses the data of only one lane)
TransCumPlot.m	Generates a figure where transformed cumulative counts curves of various LDs are plotted
TraOscillationsSpeed.m	Creates various speed figures of different LDs in order to study the traffic oscillations
TravelTimeIndex.m	Given a time it generates a table with the travel time indexes of all the highway